

Optimised Scour Protections for Offshore Hybrid Structures

JOÃO RICARDO DE SÁ CHAMBEL

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Supervisor: Prof. Dr. Francisco de Almeida Taveira Pinto

Co-Supervisor: Prof. Dr. Tiago João Fazeres-Ferradosa

Prof. Dr. Pedro Lomonaco Tonda

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DEPARTMENT OF CIVIL AND GEORESOURCES ENGINEERING

Tel. +351-22-508 1901

Fax +351-22-508 1446

✉ prodec@fe.up.pt

Edited by

FACULDADE DE ENGENHARIA DA UNIVERSIDADE DO PORTO

Rua Dr. Roberto Frias

4200-465 PORTO

Portugal

Tel. +351-22-508 1400

Fax +351-22-508 1440

✉ feup@fe.up.pt

🌐 <http://www.fe.up.pt>

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***OPTIMISED SCOUR PROTECTIONS FOR HYBRID
OFFSHORE STRUCTURES***

JOÃO RICARDO DE SÁ CHAMBEL

DOCTORAL PROGRAM IN CIVIL ENGINEERING

À minha família, amigos e em memória de
Albertina Pinto de Castro,
João Baptista Chambel e Paulo David Flores Barata

*“Since you are not experienced in things of the world,
All things that are a bit difficult seem impossible to you.”*
“Trust time. It usually provides a sweet way out of many bitter challenges”
Miguel de Cervantes Saavedra

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ABSTRACT

In the marine renewable energy (MRE) sector, bottom-fixed foundations remain the standard solution. In these structures, natural frequency is affected by scour, which can lead to collapse. Riprap scour protections are used as a countermeasure. The foundation and protection installation accounts for a significant portion of capital expenditure (CAPEX), often about 30% of the costs. While dynamic protections offer a cost-effective alternative to static design, current design approaches are primarily focused on monopile-related structures, neglecting scour development at more complex foundations and the hydrodynamic impact of coupled wave energy converters in hybrid structures. This thesis addresses critical gaps in the literature by evaluating the feasibility of optimised dynamic scour protection for complex and hybrid offshore structures, aiming to provide valuable insights that could help reduce the Levelized Cost of Energy (LCoE) in the future.

This research combined a probabilistic comparative analysis of *in situ* data from the Horns Rev 3 (Denmark) and Egmond aan Zee (The Netherlands) offshore wind farms with a comprehensive physical modelling test plan and the respective statistical analysis of damage distribution. The experimental study, conducted at the Faculty of Engineering of the University of Porto (Portugal) and at the Oregon State University (United States of America), aimed to assess erosion and damage caused to protected monopiles and jackets, as well as hybrid structures – a transformation performed by coupling a wave energy converter (WEC) to both structures. To accurately quantify the damage number (S_{3D}), the overlapping-circle method was applied to protected standard/hybrid monopiles and successfully adapted into a novel row-by-row overlapping methodology for protected complex/hybrid jacket foundations. The statistical analysis was used to assess the influence of mesh resolution on damage quantification. This led to the development of a new calibration protocol to adjust static and failure thresholds based on the chosen sub-area size, along with a new global scour evaluation framework based on the spatial/volumetric loss of armour-layer material.

Key findings demonstrate a severe engineering trade-off for hybrid structures: while the presence of a converter attenuates local leeward wave heights, it acts as a massive bluff body, and the variation in the upward-downward pressure generated by the converter's oscillatory motion severely intensifies near-bed maximum orbital velocities acting in the scour protection by up to 100%, when compared to non-hybrid structures. This complex interaction generates highly amplified turbulence, leading to measured damage rates that can cause premature failure. Crucially, the experimental results highlighted the inadequacy of existing empirical models, which systematically fail to predict deformation and damage due to their inability to capture the complexity of WEC-induced flow amplifications. Consequently, alternative damage metrics (*e.g.*, S_{3D}/n_s or S/t_s) and a dimensionless scour depth (S/D) predictive equation were proposed, accounting for the protection's thickness, which provides improved descriptors of the scour protection behaviour.

Ultimately, by providing a comprehensive framework for evaluating damage in complex and hybrid offshore structures, this research aimed to answer to some of the gaps identified in the literature and provide one of the first databases of large-scale testing in protected hybrid offshore structures, that can support the development of safer, more sustainable, resilient, and economical projects in the future, which are essential for the continuous optimisation of the MRE sector.

KEYWORDS: Scour Protections, Offshore Hybrid Structures, Complex Foundations, Marine Renewable Energy, Physical Modelling, Statistical Analysis.

RESUMO

No setor das energias renováveis marinhas (MRE), as fundações fixas são a solução mais comum. Neste tipo de estrutura, a frequência natural é afetada por erosões localizadas, que podem levar ao colapso. As proteções com recurso a enrocamento (*riprap*) são utilizadas como medida preventiva. A instalação da fundação e respetiva proteção correspondem a uma parcela importante das despesas de capital (CAPEX), cerca de 30% dos custos. Embora o conceito de proteção dinâmica ofereça uma alternativa económica às proteções estáticas, o seu dimensionamento está, na sua maioria, relacionado com monopilares, negligenciando o modo como as erosões localizadas se desenvolvem em fundações complexas e o possível impacto dos conversores de energia das ondas acoplados a estruturas híbridas. Esta tese de doutoramento aborda algumas das principais lacunas identificadas na literatura ao avaliar a viabilidade de proteções dinâmicas para estruturas offshore de geometria complexa e híbrida, com o objetivo de fornecer esclarecimentos que contribuam para reduzir o custo nivelado de energia (LCoE), no futuro.

Esta investigação combinou uma análise probabilística de dados *in situ* dos parques eólicos offshore Horns Ver 3 (Dinamarca) e Egmond aan Zee (Países Baixos) com testes de modelação física e respetiva análise estatística da distribuição do dano. Os ensaios experimentais, realizados na Faculdade de Engenharia da Universidade do Porto (Portugal) e na Oregon State University (Estados Unidos da América), tiveram como objetivo avaliar o dano em proteções aplicadas a monopilares e a fundações do tipo jacket, bem como em fundações híbridas – transformação realizada por meio do acoplamento de um conversor de energia das ondas (WEC). Para quantificar com precisão o número de dano (S_{3D}), foi aplicado o método de sobreposição de círculos (subárea) a proteções circulares em monopilares (híbridos) e adaptado para avaliar, com sucesso, proteções não circulares em jackets (híbridos). A análise estatística foi utilizada para determinar a influência da resolução da malha de análise na quantificação do dano. Assim, foi desenvolvido um novo protocolo de calibração para ajustar os limites de comportamento estático/falha, com base no tamanho da subárea selecionada, bem como uma nova avaliação do estado global da proteção, com base na perda espacial/volumétrica do material que compõe o manto resistente.

A principal conclusão deste estudo indica que, embora o conversor de energia atenuasse as alturas de onda locais a sotavento, as suas dimensões e a variação de pressão ascendente-descendente gerada pelo movimento dos seus elementos aumentam as velocidades orbitais de pico junto à proteção em até 100%, face a estruturas não híbridas. Este aumento de turbulência gera danos consideráveis, podendo levar à falha prematura da proteção. Os resultados também apontam para a inadequação dos modelos empíricos atuais, que falham na previsão de deformações e danos por não captarem a complexidade e a amplificação do escoamento induzidas pelo conversor. Assim, foram propostos novos parâmetros (*e.g.*, S_{3D}/n_s ou S/t_s) e uma nova equação para a profundidade de erosão relativa (S/D) que integram a espessura da proteção, fornecendo indicadores mais adequados ao comportamento de proteções contra erosões localizadas.

Ao fornecer um enquadramento abrangente para a avaliação de dano em estruturas offshore complexas e híbridas, este estudo pretendeu dar resposta a algumas das lacunas identificadas na literatura e fornecer uma das primeiras bases de dados de testes de larga escala para proteções em estruturas offshore híbridas, que possam servir de suporte ao desenvolvimento futuro de projetos mais seguros, sustentáveis e resilientes para a transição para o setor da energia renovável marinha.

PALAVRAS-CHAVE: Proteções contra Erosões Localizadas, Estruturas Híbridas Offshore, Fundações Complexas, Energias Renováveis Marinhas, Modelação Física, Análise Estatística.

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NOMENCLATURE

SYMBOLS

A	[-]	Reference distance relative to the structure's footprint length – Equation (10a)
A_{front}	[-]	Reference distance relative to structure's upstream side – Equation (10b)
$A_{L\%}$	[%]	Acceptable spatial Loss
A_n	[-]	Equation additional term – Equation (26b)
A_{pile}	[m ²]	Cross-sectional area of the monopile
A_{pile_jacket}	[m ²]	Cross-sectional area of a jacket pile
$A_{protection}$	[m ²]	Surface area of the scour protection
A_{rear}	[-]	Reference distance relative to structure's downstream side – Equation (10c)
A_{sub}	[m ²]	Sub-area (overlapping-circle method)
a_0	[-]	Regression fitting coefficient – Equation (4)
a_1	[-]	Coefficient for hydrodynamic conditions – Equation (4)
a_2	[-]	Regression fitting coefficient – Equation (4)
a_3	[-]	Regression fitting coefficient – Equation (4)
a_4	[-]	Coefficient for hydrodynamic conditions – Equation (4)
B	[-]	Jacket lowest node distance impact coefficient – Equation (10a)
B'	[-]	Equation additional term – Equation (12b)
B_n	[-]	Equation additional term – Equation (26c)
b_0	[-]	Regression fitting coefficient – Equation (4)
C	[m]	Tip clearance distance
C_f	[-]	Correction factor
C'	[-]	Equation additional term – Equation (12b)
c_1	[-]	Regression fitting coefficient – Equation (13a)
c_2	[-]	Regression fitting coefficient – Equation (13a)
c_3	[-]	Regression fitting coefficient – Equation (13a)

D	[m]	Diameter
D^*	[-]	Dimensionless grain size
D_{cr}	[m]	Critical grain size
D_{base}	[m]	Diameter of a non-uniform cylindrical structure
D_{jacket}	[m]	Jacket pile diameter
D_{n50}	[m]	Nominal stone diameter of the scour protection
D_p	[m]	Monopile diameter
D/L	[-]	Relative pile size
D_t	[m]	Turbine disc diameter
D_{15}	[m]	15 th percentile of scour protection grading
D_{50}	[m]	Mean stone diameter of the scour protection
$D_{67.5}$	[m]	67.5 th percentile of scour protection grading
D_{85}	[m]	85 th percentile of scour protection grading
d	[m]	Water depth
d_s	[m]	Diameter of the sediments
Eu	[-]	Euler number
e	[J]	Internal energy
Fr	[-]	Froude number
F	[N]	External forces
g	[m/s ²]	Gravitational acceleration
H	[m]	Wave height
H_m	[m]	Mean wave height
H_{m0}	[m]	Spectral significant wave height
$H_{max,50}$	[m]	Maximum wave height for a 50-year return period
H_r	[m]	Height/Radius of the turbine rotor
H_{rms}	[m]	Wave height root mean square
H_s	[m]	Significant wave height

$H_{s,50}$	[m]	Significant wave height for a 50-year return period
h	[m]	Water level
K_{Red}	[%]	Wave reduction coefficient
K_T	[%]	Wave transmission coefficient
KC	[-]	Keulegan-Carpenter number (waves)
KC_c	[-]	Keulegan-Carpenter number (currents)
KC_{tot}	[-]	Total Keulegan-Carpenter number
k	[m ² /s ²]	Turbulent kinetic energy
L	[m]	Wavelength
MOB	[-]	Mobility parameter
MOB_{top}	[-]	Mobility parameter on top of the armour layer
N	[-]	Number of waves
n_s	[-]	Number of rock stone size layers
P_f	[-]	Probability of failure
P_{99}	[-]	99 th percentile
P_{95}	[-]	95 th percentile
P_{90}	[-]	90 th percentile
p	[N/m ²]	Fluid pressure
Q	[J]	Heat-supplied energy
R^2	[-]	Coefficient of determination
Re	[-]	Reynolds number
Re_D	[-]	Structure Reynolds number
S	[m]	Scour depth
S_{eq}	[m]	Equilibrium scour depth
S/D	[-]	Relative scour depth
S/D_{column}	[-]	Maximum relative scour depth under the column
$S/D_{predicted}$	[-]	Predicted relative scour depth

S/t_s	[-]	Scour depth to protection thickness ratio
S_{max}/D	[-]	Maximum relative scour depth
$S_{predicted}/D$	[-]	Predicted relative scour depth
S_{3D}	[-]	Damage number
$S_{3D,FTE}$	[-]	Failure threshold estimation for the damage number
$S_{3D,failure}$	[-]	Failure threshold for the damage number
$S_{3D,max}$	[-]	Maximum damage number
$S_{3D,mean}$	[-]	Mean damage number
$S_{3D,measured}$	[-]	Measured damage number
$S_{3D,min}$	[-]	Minimum damage number
$S_{3D,predicted}$	[-]	Predicted damage number
$S_{3D,static}$	[-]	Static threshold for the damage number
S_{3D}/n_s	[-]	Damage ratio
s	[-]	Relative density (ρ_s/ρ_w)
$stab$	[-]	Stability parameter
T	[s]	Wave period
T_m	[s]	Mean wave period
$T_{m-1,0}$		Energy wave period
T_p	[s]	Wave peak period
$T_{p,50}$	[s]	Wave peak period for a 50-year return period
T'	[K]	Temperature
T^*	[-]	Dimensionless time scale
t_s	[m]	Scour protection thickness
t_s/d	[-]	Relative protection thickness
U_c	[m/s]	Depth-averaged current velocity
$U_{c,50}$	[m/s]	Depth-averaged current velocity for a 50-year return period
$U_{c,ground50}$	[m/s]	Seabed current velocity for a 50-year return period

U_{cr}	[m/s]	Mean threshold velocity of sediments
U_{cw}	[-]	Current-Wave velocity ratio
U_m	[m/s]	Orbital bottom velocity
$U_{m,s}$	[m/s]	Significant orbital bottom velocity
$U_{m,max}$	[m/s]	Peak orbital bottom velocity
U_{max}	[m/s]	Vortices local maximum velocity
Ur	[-]	Ursell number
u	[m/s]	Flow velocity
$V_{A,i}$	[m ³]	Cumulative erosion volume
$V_{A,max}$	[m ³]	Maximum erosion volume
V_{Area}	[m ³]	Analysed scoured area volume factor
V_T	[m ³]	Total volume
V_e	[m ³]	Eroded volume
$V_{L\%}$	[%]	Acceptable volume loss
w_s	[m/s]	Settling velocity
α	[-]	Amplification factor
α'	[°]	Flap rotation angle
$\alpha_{Um,s}$	[-]	Significant orbital bottom velocity ratio
$\alpha_{Um,max}$	[-]	Maximum orbital bottom velocity ratio
$\Delta S_{3D}/n_s$	[-]	Damage increase ratio
ζ	[-]	Reynolds-related parameter (function of hydrodynamic conditions)
$\eta_{S3D,grid}$	[-]	Grid ratio for the overlapping-circle mesh
θ_{cr}	[-]	Critical Shields parameter
θ_{max}	[-]	Dimensionless maximum wave-current-induced shear stress
λ_{static}	[-]	Static threshold ratio
μ	[Pa·s]	Dynamic viscosity
ν	[m ² /s]	Kinematic viscosity

ρ	[kg/m ³] Fluid mass density
ρ_s	[kg/m ³] Rock material mass density
ρ_w	[kg/m ³] Water mass density
σ_{S3D}	[-] Standard deviation for the damage number
τ	[N/m ²] Stressor tensor
τ_{cr}	[N/m ²] Critical bed shear stress
τ_m	[N/m ²] Mean combined bed shear stress (current and wave-induced)
τ_{max}	[N/m ²] Maximum combined bed shear stress (current and wave-induced)
γ	[-] Wave spectrum peak enhancement factor
∇	[m ⁻¹] Vector differential operator

ABBREVIATIONS

ADV	Acoustic Doppler Velocimetry
CAPEX	Capital Expenditure
CC	Climate Changes
CFD	Computational Fluid Dynamics
DECG	Department of Civil Engineering and Georesources
DAQ	Data Acquisition System
DEM	Discrete Element Method
DNS	Direct Numerical Simulations
DOF	Degree of Freedom
DTM	Digital Terrain Model
EU	European Union
FEUP	Faculty of Engineering of the University of Porto
FOSWEC	Floating Oscillating Wave Surge Energy Converter
FOWT	Floating Offshore Wind Turbine
GBF	Gravity-Based Foundations

GBS	Gravity-Based Structure
HACC	Hexagonal Array of Circular Cylinders
HWRL	O.H. Hinsdale Wave Research Laboratory
J	Jacket
JH	Jacket (Hybrid)
JONSWAP	Joint North Sea Wave Project
LCoE	Levelized Cost of Energy
LES	Large Eddy Simulations
LH-SHRHA	Hydraulic Laboratory of the Hydraulics, Water Resources, and Environmental Division
LiDAR	Light Detection and Ranging
LNG	Liquefied Natural Gas
LWF	Large Wave Flume
M	Monopile
MH	Monopile (Hybrid)
MRE	Marine Renewable Energy
MTA	Multiple Transducer Array
NSE	Navier-Stokes Equations
NWT	Numerical Water Tanks
OF	Offshore Foundations
OHS	Offshore Hybrid Structure
OHVS	Offshore High Voltage Station
OS	Offshore Structure
OSU	Oregon State University
OPTI-PILE	Optimisation of Monopile Foundations for Offshore Wind Turbines in Deep Water and North Sea Conditions
OW	Offshore Wind

OWC	Oscillating Water Column
OWE	Offshore Wind Energy
OWSEC	Oscillating Wave Surge Energy Converter
OWT	Offshore Wind Turbine
PTO	Power-Take-Off
PWAS	Passive Wave Absorption System
RANS	Reynolds-Averaged Navier-Stokes
RMSE	Root Mean Square Error
RNG	Renormalisation Group
SST	Shear Stress Transport
TACC	Triangular Array of Circular Cylinders
TCP	Tension Leg Platform
TEAMER	Testing and Expertise for Marine Energy
TEC	Tidal-Current Energy Converter
TLP	Tension Leg Platform
USAF	Umbrella Suction Anchor Foundation
URANS	Unsteady Reynolds Averaged Navier-Stokes
VARANS	Volume Averaged Reynolds-Averaged Navier Stokes
VOF	Volume of Fluids
WC	Waves and Currents
WEC	Wave Energy Converter
WI	Waves (Irregular)
WG	Wave Gauge
WR	Waves (Regular)

1. Introduction

1.1. BACKGROUND AND MOTIVATION

As one of the most appealing forms of clean energy, the offshore wind energy (OWE) sector has been recognised as a vital component of the future of renewables and the transition to cleaner energy, especially considering European efforts and policies to achieve net-zero carbon emissions by 2050 (WindEurope, 2021a). The OWE has seen increased demand due to sector expansion and improved competitiveness, driven by more efficient, mature technologies and a continuous decrease in LCoE.

It is anticipated that by 2030, bottom-fixed and floating offshore wind turbines (OWT) will see an LCoE decrease of 44% to 48 €/MWh and 65% to 69 €/MWh, respectively, compared to 2020, which is significantly less than the 150 €/MWh value of the 2010s (WindEurope, 2021a, 2022a). To achieve climate neutrality, wind energy must fulfil 25% of the European Union (EU) demand by 2030 and 50% by 2050 (with 17% from offshore wind energy, or OWE), with 81% of energy sourced from renewables (WindEurope, 2021a). In a short timeframe, a total wind energy capacity of 453 GW will be required, including 79 GW of OWE (WindEurope, 2022b). To reach this target, it is essential to install at least 27.9 GW of offshore wind power between 2022 and 2026, averaging nearly 8.5 GW per year – a substantial increase compared to the 3.4 GW installed in 2021 (WindEurope, 2022b).

In fixed Offshore Wind (OW) installations, the foundation typically accounts for around 30% of the total investment (Bhattacharya, 2014; Matutano *et al.*, 2013). In these structures, the natural frequency is influenced by scour, which could lead to collapse (Matutano *et al.*, 2013). Riprap protections are employed as a countermeasure against scour, making them an essential part of the investment (Fazeres-Ferradosa *et al.*, 2019b). Due to the complexity of the offshore environment, understanding the influence of foundation and protection design is crucial for optimisation, leading to decreased overall investment and lower LCoE. Over the past decade, significant progress has been made in scour protection solutions, particularly the development of dynamic scour protections (Fazeres-Ferradosa *et al.*, 2019b), which could be applied to complex foundations, WECs, tidal-current energy converters (TECs), and eventually offshore hybrid structures (Fazeres-Ferradosa *et al.*, 2021).

Industrial stakeholders keep the implementation of some developments and novel design methods for scour protection private. However, specific aspects need to be addressed, as they can significantly influence optimised designs and their application in offshore hybrid structures (OHS). These issues include scour patterns and scour protections for complex foundations and new geometries, the effects of extending offshore wind turbine lifecycles on existing structures, how repowering or more powerful turbines might alter foundation dimensions and, consequently, scour protection designs, and the impact that WECs or TECs have on the flow field, seabed, and protections (Fazeres-Ferradosa *et al.*, 2021).

Although literature includes studies on scour around WECs and TECs, such as De Vos *et al.* (2011), Sumer *et al.* (2001), and Whitehouse *et al.* (2011a), to the authors' knowledge, no research has focused on the use of dynamic protections at OHS. Energy converters may alter the hydrodynamics around structures, they cause changes in wave orbital motion, depth-averaged current velocity, bed shear stress, and pressure acting on the seabed or within the armour layer of the protection. The extent of this influence remains to be quantified.

Most studies regarding scour phenomena (Fredsoe and Deigaard, 1992; Sumer *et al.*, 1992; Sumer and Fredsøe, 2001; Sutherland and Whitehouse, 1998; Whitehouse, 1998; Whitehouse *et al.*, 2010) or damage in scour protections (De Vos, 2008; De Vos *et al.*, 2011, 2012; den Boon *et al.*, 2004; Fazeres-Ferradosa, 2018) have been conducted using physical modelling. These studies primarily focused on monopile foundations and paid less attention to other complex geometries, even overlooking other marine harvesting technologies. Recently, new methods have been developed that allow for the detailed and accurate description of scour and damage, with reduced margins of error (Fazeres-Ferradosa *et al.*, 2020). While offshore standard foundations are well documented, complex or hybrid structures, as well as marine energy converters, pose significant challenges and knowledge gaps regarding scour protection and sediment transport, warranting further investigation. There is a pressing need to analyse scour countermeasures for these structures with complex geometries and features. Additionally, the optimisation of multiple marine harvesting technologies integrated into a single unit and their subsequent impacts on seabed sediment erosion remains largely unexplored.

Addressing these gaps is essential to ensuring the long-term resilience of riprap scour protection, offshore structures, and marine energy converters, especially amid escalating environmental conditions. This research aims to address the identified challenges by utilising multi-scale, high-resolution experimental physical model data and developing a damage analysis methodology. In doing so, this work contributes to the future development of resilient scour protection strategies, potentially supporting innovations in ocean engineering.

1.2. OBJECTIVES AND NOVELTY

The primary aim of this thesis is to address the identified challenges through a statistical analysis that complements a comprehensive experimental study of physical modelling. This research combines small- and large-scale testing to evaluate damage to scour protection systems installed on monopiles, jackets, and hybrid structures. Specifically, this thesis aims to clarify the complex hydrodynamic interactions among wave and current actions, sediments, riprap armour layers, and the impact of implementing an oscillating surge wave energy converter (OSWEC). The detailed objectives are as follows:

- **Probabilistic analysis of *in situ* data:** to apply a probabilistic methodology to account for uncertainty and assess the reliability of existing scour protection mechanisms using data from the Horns Rev 3 and Egmond aan Zee offshore wind farms. This includes exploring the potential to optimise the armour layer material size (nominal median stone size, D_{n50}) for scour protection.
- **Application of the overlapping-circle method:** to conduct a small-scale physical model testing on protected monopiles under various hydrodynamic conditions to examine armour layer units' displacement and to compute the damage number by means of the overlapping-circle method. This objective aims to evaluate the method as a capable design tool, assess the stability of dynamic protections, propose acceptable damage-behaviour thresholds, and identify limitations in existing predictive formulas, such as the failure to consider armour-layer thickness.

- **Application of scour protection to complex foundations (jacket):** to analyse S_{3D} for scour protection configurations explicitly designed for a 4-leg jacket foundation model, building upon the results and considerations reported by Welzel *et al.* (2020) and Sarmiento *et al.* (2021).
- **Application of scour protections to hybrid structure:** to examine the influence of harvesting technologies on scour protection behaviour by testing a monopile and a jacket coupled with an OSWEC. This involves analysing how the presence of the converter and the movement of its paddles alter hydrodynamics and how those effects affect the development of armour-layer damage.
- **Large-scale experimental tests:** to improve the knowledge on damage and the converter's influence on scour-generating flow mechanism by conducting a large-scale experimental study on monopiles and hybrid monopiles. The aim is to assess the behaviour of two different scour protection designs by incorporating a late-stage converter model developed by OSU.
- **Development of a new damage analysis methodology for complex/hybrid structures:** to create a new overlapping method that allows the accurate calculation of S_{3D} for complex and hybrid offshore structures. Based on the overlapping-circle method of Fazerer-Ferradosa *et al.* (2020), the new approach is designed to account for versatility, allowing the application to variable geometries and non-conventional scour protection setups.
- **Statistical analysis and presentation of new damage evaluation frameworks:** to establish the overlapping concept as a generalised approach for various scour protection layouts and types of offshore structures, a spatial/volumetric loss approach (for global scour) and a threshold calibration protocol (for local scour) are proposed, and an example is given as a proof of concept.

The novelty of this research lies in the physical modelling of scour protections applied to complex and hybrid structures – specifically jackets, hybrid monopiles, and hybrid jackets – complemented by large-scale testing; a novel overlapping damage analysis approach developed to address enduring challenges in the field when dealing with complex or non-standard geometries; and a thorough statistical analysis of the results that led to the proposal of two frameworks. When combined, these frameworks enable evaluation of damage from both global and local scour. This research contributes to more accurate monitoring and improved prediction of damage and failure in protective systems and foundations with standard and complex geometries, thereby supporting the future design and monitoring of more resilient offshore infrastructure.

1.3. THESIS OUTLINE

This thesis is organised into eight chapters, summarised in this section. Chapter 1 provides a brief introduction to the subject, background, motivation, and objectives of the PhD. The literature review is discussed in Chapter 2, focusing on scour and scour protection for complex bottom-fixed offshore and marine renewable energy structures, and highlighting the significant gaps identified with respect to the PhD's central theme and objectives of the PhD. It also covers the probabilistic analysis of current *in situ* scour protection mechanisms to explore the potential to optimise the dimensions of armour-layer units. Chapter 3 describes the laboratory facilities, equipment, physical model testing programme, and procedures used at both the Hydraulics, Water Resources, and Environment Division (LH-SHRHA) laboratory of the Department of Civil and Georesources Engineering (DECG) at FEUP and the OH Hinsdale Research Laboratory at OSU. In Chapter 4, the overlapping-circle method proposed by Fazerer-Ferradosa *et al.* (2020) is applied to results from small-scale physical model tests on riprap-

protected monopile foundation and hybrid monopile structure, thereby validating its capabilities. Chapter 5 presents the results of small-scale physical model tests on riprap-protected jacket foundation and hybrid jacket structure, utilising a novel damage analysis tool specifically developed for foundations and protection systems with variable geometry. Chapter 6 introduces a new damage method for analysing experimental results from complex/hybrid structures, along with a more detailed statistical analysis, and proposes two new frameworks for analysing damage. The large-scale test outcomes from the wave flume at the OH Hinsdale Research Laboratory are reported in Chapter 7, including an in-depth analysis of not only the scour protection but also the performance of the chosen converter. Finally, Chapter 8 presents the study's conclusions and recommendations for future research.

The results of the thesis were published in the following journals:

- Chambel, J., Fazerer-Ferradosa, T., Figueiredo, R., Rosa-Santos, P., and Taveira-Pinto, F. (2022), “*Probabilistic Assessment and Comparison of Scour Protections at Horns Rev 3 and Egmond aan Zee Offshore Wind Farms*”, ISSMGE: International Journal and Database of Geoenvironment and Histories (<https://doi.org/10.4417/IJGCH-07-04-05>) – no. citations: 3.
- Chambel, J., Fazerer-Ferradosa, T., Miranda, F., Bento, A.M., Taveira-Pinto, F., and Lomonaco, P. (2024), “*A Comprehensive Review on Scour and Scour Protections for Complex Bottom-Fixed Offshore and Marine Renewable Energy Foundations*”, Ocean Engineering (<https://doi.org/10.1016/j.oceaneng.2024.117829>) – Q1 journal, no. citations: 70.
- Chambel, J., Fazerer-Ferradosa, T., Welzel, M., Taveira-Pinto, F., and Lomonaco, P. (2025), “*Comparative Analysis of Scour in Riprap-Protected Monopiles and Hybrid Foundations*”, Journal of Marine Science and Engineering (<https://doi.org/10.3390/jmse13091639>) – Q2 journal, no. citations: 4.
- Chambel, J., Fazerer-Ferradosa, T., Alemi, M., Taveira-Pinto, F., and Lomonaco, P. (2026a), “*Damage Characterisation of Scour in Riprap-Protected Jackets and Hybrid Foundations*”, Journal of Marine Science and Engineering (<https://doi.org/10.3390/jmse14020114>) – Q2 journal, no. citations: 2.
- Chambel, J., Fazerer-Ferradosa, T., Romão, X., Alemi, M., Taveira-Pinto, F., and Lomonaco, P. (2026b), “*New Damage Quantification Method for Protected Complex Offshore Foundations: Statistical Analysis*”, ICE: Maritime Engineering (<https://doi.org/10.1680/jmaen.26.00006>) – Q2 journal, no. citations: 1.

The research findings and other related studies were further disseminated through the following conference publications and symposium presentations:

- Chambel, J., Sarkar, A., Ishtiyak, M., Fazerer-Ferradosa, T., Rosa-Santos, P. and Taveira-Pinto, F. (2022), “*Extending the Application of Offshore Wind Monopiles to Intermediate Water Depths*”, Proceedings of the 7th IAHR Europe Congress, Athens, Greece (ISBN: 978-618-85675-3-5).
- Chambel, J., Fazerer-Ferradosa, T., Bento, A.M., Taveira-Pinto, F., and Lomonaco, P. (2023), “*Experimental Study of Long-Term Scour Damage for Protected Offshore Wind Foundations*”, Advances in the Analysis and Design of Marine Structures - Proceedings of the 9th International Conference of Marine Structures (MARSTRUCT), Gothenburg, Sweden (<https://doi.org/10.1201/9781003399759-26>).

- Chambel, J., Fazeres-Ferradosa, T., Miranda, F., Bento, A.M., Rosa-Santos, P., and Taveira-Pinto, F., (2023) “*The Adaptation of a Current Flume to a Wave-Current Flume for Coastal Studies*”, Proceedings of the 40th IAHR World Congress, Vienna, Austria (https://doi.org/10.3850/978-90-833476-1-5_iahr40wc-p0005-cd).
- Chambel, J., Fazeres-Ferradosa, T., Miranda, F., Bento, A.M., Rosa-Santos, Lomonaco, P., and Taveira-Pinto, F. (2023), “*Comparison of Scour in Complex Soils around the Foundations of Marine Harvesting Technologies*”, Proceedings of the 11th International Conference of Scour and Erosion (11-ICSE), Copenhagen, Denmark. Society of Soil Mechanics and Geotechnical Engineering (ISSMGE): London, UK.
- Chambel, J., Fazeres-Ferradosa, T., Lomonaco, P., and Taveira-Pinto, F. (2025), “*Analysis of Damage in Scour Protections for Hybrid Offshore Wind Turbine Foundations*”, INORE Symposium 2025, Aalborg, Denmark.

The author also contributed as a co-author to the following publications that are related to this thesis:

- Figueiredo, R., Fazeres-Ferradosa, T., Chambel, J., Rosa-Santos, P., and Taveira-Pinto, F. (2022), “*Comparative Analysis of Available Wave Hindcast Models for the North Sea and their Influence on the Design of Offshore Scour Protections*”, Proceedings of the 39th IAHR World Congress, Granada, Spain (<https://doi.org/10.3850/IAHR-39WC2521711920221808>).
- Figueiredo, R., Fazeres-Ferradosa, T., Chambel, J., Rosa-Santos, P., and Taveira-Pinto, F. (2022), “*How does the Selection of Wave Hindcast Datasets and Statistical Models Influence the Probabilistic Design of Offshore Scour Protections*”, Ocean Engineering (<https://doi.org/10.1016/j.oceaneng.2022.113123>) – Q1 journal, no. citations 3.
- Miranda, F., Chambel, J., Bento, A.M., Taveira-Pinto, F., Rosa-Santos, P., and Fazeres-Ferradosa, T. (2023), “*Wave-Current Flume Dissipation System Reflection Analysis*”, Proceedings of the 16^o Congresso da Água, Lisbon, Portugal (ISBN: 978-989-8509-32-1).
- Miranda, F., Bento, A.M., Chambel, J., Sarmiento, M.F., Rosa-Santos, P., Taveira-Pinto, F., and Fazeres-Ferradosa, T. (2023), “*A Novel and Simple Passive Absorption System for Wave-Current Flumes*”, Alexandria Engineering Journal (<https://doi.org/10.1016/j.aej.2023.03.067>) – Q1 journal, no. citations 12.
- Miranda, F., Bento, A.M., Chambel, J., Fazeres-Ferradosa, T., Rosa-Santos, P., and Taveira-Pinto, F. (2024), “*Investigation of Wave Reflection at Different Water Heights in a Wave-Current Flume*”, in: Pavlou, D. et al. “*Analytical and Experimental Methods in Mechanical and Civil Engineering*”. OES 2023. Structural Integrity, vol 28, Springer (https://doi.org/10.1007/978-3-031-49723-0_6).

2. Scour Protections for Offshore and Marine Structures

2.1. INTRODUCTION

This chapter provides a literature review of the topics covered in this thesis: optimised scour protection for offshore hybrid structures. It includes an overview of topics covering existing studies and knowledge gaps. A more detailed description of the topics presented in this chapter was published in Chambel *et al.* (2022, 2024). Hereafter, a summary of the most relevant information is presented.

2.2. OFFSHORE STRUCTURES AND FOUNDATIONS

In today's world, climate change (CC) is a focal point of modern society and an alarming problem that has increasingly interfered with people's lives. One of the major contributors to the increased severity of the CC effects is the consumption of non-renewable energy sources. As previously mentioned, the OWE sector is one of the most alluring forms of renewable energy and has been experiencing significant growth to counter CC and reduce reliance on fossil fuels. Another sector in clear expansion, with tremendous potential and commercial development at the present state of the art, is the marine harvesting technologies sector. The combination of these two technologies could lead to a significant reduction in costs while increasing energy production. They are referred to as offshore structures (OS), and their installation involves the use of specific offshore foundations (OF).

As the term 'offshore' suggests, OSs and/or OFs are implemented in the marine environment, detached from the coast and at a relative distance from it. They are used for multiple purposes, with some implementations on fixed platforms and others on floating platforms – such as production, storage, and offloading platforms, as well as oil/gas rigs, offshore high-voltage stations (OHVS), and OWT (Amaechi *et al.*, 2022; Haritos, 2007).

Regarding OWTs, their foundations can have different configurations and can be placed in a wide range of water depths (Figure 1), thus being divided into two major groups:

- **Bottom-fixed foundations:** foundations fixed on the seabed. Monopiles are the most used, placed mainly in shallow waters (up to 30 m deep). Other, more complex foundations, such as jackets, tripods, and Gravity-Based foundations (GBF), are better suited for transitional waters (to depths of 50 to 60 m). According to WindEurope (2021b), complex foundations account for 18.8% of the OWT foundations in Europe (Figure 2) – jackets (9.9%), GBFs (5%), tripods (2.2%), and tripile (1.4%).
- **Floating offshore wind turbines (FOWT):** OWT with floating platforms attached to the seabed by mooring lines and anchors, including barge, semi-submersibles, Spar buoys, and

tension leg platforms (TLPs). They represent 0.2% of the OWT foundations in Europe (WindEurope, 2021b).

Since the marine environment consists of movable seabeds with either cohesive or non-cohesive properties and hydrodynamic conditions that can vary significantly, the presence of these foundations induces significant changes in flow. Interactions between the flow and the structure increase bed shear stress, local velocities, and flow-induced turbulence, thereby initiating sediment transport. When the critical bed shear stress is exceeded, the scour process starts (De Vos *et al.*, 2011; Sørensen and Ibsen, 2013; Sumer *et al.*, 2001; Whitehouse *et al.*, 2011a).

Scour is the generalised erosion of the seabed in the surrounding structure area, resulting from the interaction among soil, flow, and the structure. It is the leading cause of structural failure at ultimate service limit states. With the rise in mean sea level and the increasing frequency of extreme events (higher significant wave height, peak wave period, flow velocities, etc.) due to CC, scour protection plays a critical role in OWT design and overall costs.

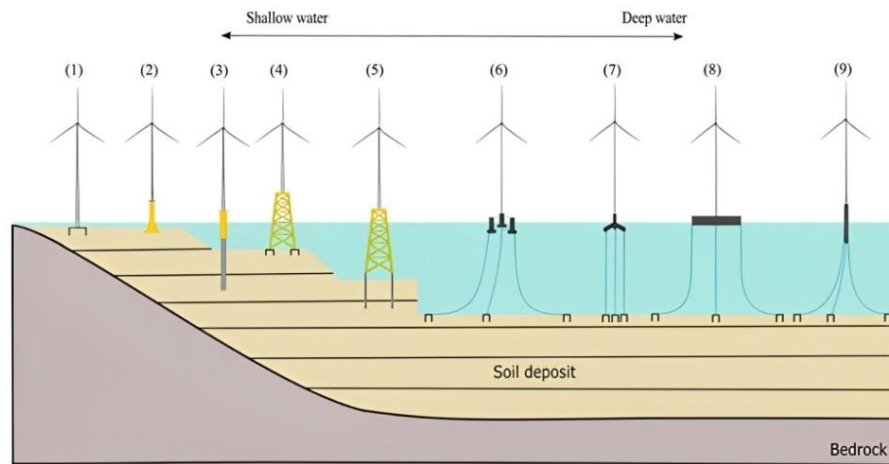


Figure 1 - Types of OWT foundations for different water depths (Bhattacharya *et al.*, 2023): (1) through (5) – bottom-fixed foundations, (6) through (9) – FOWT foundations.

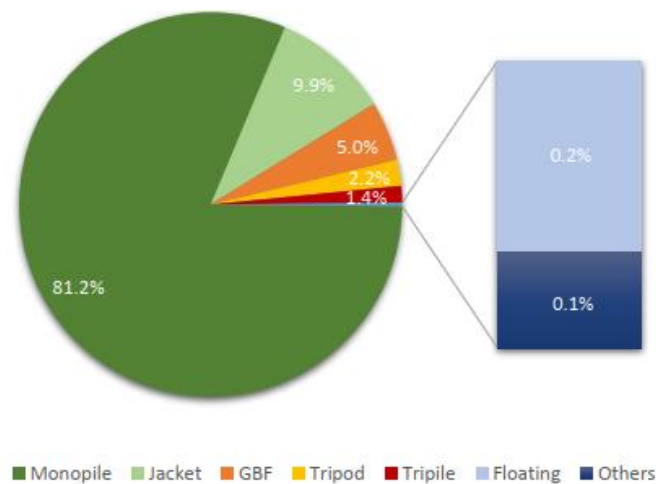


Figure 2 - OWT foundations installed in Europe (WindEurope, 2021b).

2.3. OFFSHORE SCOUR PROTECTIONS: DESIGN METHODOLOGIES

Various studies have been conducted on distinct scour countermeasures (Corvaro *et al.*, 2018; Fazeres-Ferradosa *et al.*, 2019a; Vahdati *et al.*, 2020). Nevertheless, riprap protections (Figure 3), inspired by rubble-mound breakwaters, placed around the foundation, are the most common solution due to their high availability and low cost (De Vos, 2008; Fazeres-Ferradosa *et al.*, 2019b).

Scour protective measures and their costs are highly susceptible to location, material size, availability, transport, and installation, as well as to marine environmental conditions, including water depth, wave characteristics, current velocity and direction, wave-current interaction, tides, storm surges, and storm durations, among others (Fazeres-Ferradosa *et al.*, 2021). Riprap protections are usually classified by design concept and divided into three major groups, as stated by De Vos *et al.* (2011, 2012) and Schendel (2018).

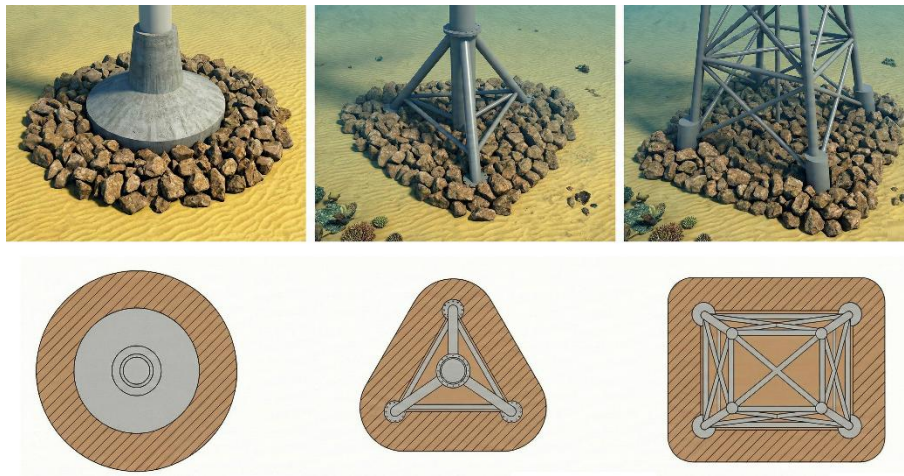


Figure 3 - Scheme of riprap scour protections for different offshore foundations: Gravity-Based Foundation (left), Tripod (centre), Jacket (right).

2.3.1. STATIC PROTECTIONS

According to Fazeres-Ferradosa *et al.* (2021), static protections are the most used type of scour protection in commercial offshore wind projects. Its design concept is based on the threshold of motion, which mentions that the critical stone size (D_{cr}) should be determined so that the shear stress introduced by environmental conditions is smaller than the critical shear stress of the protection material, *i.e.*, the movement of the elements of the armour layer units is not allowed.

Soulsby (1997) developed one of the most common design formulas (Equation 1), where the mass density of the material (ρ_s) directly impacts the median stone size (D_{50}) used – τ_{cr} is the critical bed shear stress, ρ_w is the water mass density. θ_{cr} is the critical Shields parameter, which for non-cohesive soils, a dimensionless grain size (D^*) larger than 100 has an asymptotic value of 0.056.

To consider the effects that monopiles or other complex foundations produce on the increase of wave-current shear stress, an amplification factor (α) must be included. This factor converts the ratio of disturbed to undisturbed bed shear stress conditions. Whitehouse (1998) and Sumer and Fredsøe (1997) have extensively studied the values of α for monopiles. However, for complex structures, those values

cannot be directly extrapolated. Therefore, the static design of scour protection and the corresponding α values for complex foundations constitute a significant knowledge gap in the literature.

$$\tau_{cr} = \theta_{cr} \cdot g \cdot (\rho_s - \rho_w) \cdot D_{50} \quad (1)$$

$$D^* = \left(\frac{g \cdot (s - 1)}{v^2} \right)^{1/3} d_s \quad (2)$$

2.3.2. DYNAMIC PROTECTIONS

Although not extensively used in commercial offshore projects, or at least not publicly disclosed, this type of protection enables the controlled movement of the elements within the armour layer. It has been the focus of the scientific community for the majority of the last two decades. They represent an upgrade to the static design method, as the reduction in D_{50} achieved results in economic savings.

The first reference to the concept of dynamic scour protection was made by den Boon *et al.* (2004) in the OPTI-PILE project. The authors proposed a design methodology introducing the so-called stability parameter (*stab*) – the ratio between the maximum dimensionless wave-current-induced shear stress (θ_{max}) and the dimensionless critical shear stress,

$$stab = \frac{\theta_{max}}{\theta_{cr}} \quad (3)$$

The failure criteria were defined when the filter layer had an exposure area equal to, or larger than, $4D_{50}^2$ – *i.e.*, an area equivalent to a square formed by two stones of size D_{50} per side. Thus, a relation between the *stab* values and the criteria of failure allowed for the definition of three distinctive levels of stability/failure (den Boon *et al.*, 2004):

- **Static stability:** $stab < 0.4155$.
- **Dynamic stability:** $0.4155 \leq stab \leq 0.460$.
- **Failure:** $stab > 0.460$.

As the *stab* parameter was still, to some extent, dependent on the amplified bed shear stress, De Vos (2008) and De Vos *et al.* (2012) proposed a new, alternative design methodology, based on an extensive physical modelling study program. De Vos (2008) and De Vos *et al.* (2012) also found that the *stab* parameter failed to predict dynamic behaviour across a variety of hydrodynamic conditions. Therefore, the simplified design formula (Equation 4) for damage number (S_{3D}) was introduced, based on Van der Meer's formula (Van der Meer, 1990), which is not directly dependent on the critical shear stress, thereby surpassing some of the limitations of previous design proposals.

$$\frac{S_{3D}}{N^{b0}} = a_0 \cdot \frac{U_m^3 \cdot T_{m-1,0}^2}{\sqrt{g \cdot d} \cdot (s - 1)^{3/2} \cdot D_{n50}^2} + a_1 \cdot \left(a_2 + a_3 \frac{(U_c/w_s)^2 \cdot (U_c + a_4 \cdot U_m)^2 \cdot \sqrt{d}}{g \cdot D_{n50}^{3/2}} \right) \quad (4)$$

where N is the number of waves, D_{n50} is the nominal stone diameter, g is the gravitational acceleration, d is the water depth, U_m is the wave orbital bottom velocity, $T_{m-1,0}$ is the energy wave period, s is the

ratio between ρ_s and ρ_w , U_c is the current depth-average velocity, w_s is the settling velocity, a_0 , a_2 , a_3 , and b_0 are regression coefficients equal to 0.00076, -0.022, 0.0079, and 0.243, respectively, and a_1 and a_4 are coefficients for hydrodynamic conditions defined as:

$$a_1 = \begin{cases} 0 & \text{for } \frac{U_c}{\sqrt{g \cdot D_{n50}}} < 0.92 \text{ and collinear waves and currents} \\ 1 & \text{for } \frac{U_c}{\sqrt{g \cdot D_{n50}}} \geq 0.92 \text{ or collinear waves and currents} \end{cases} \quad (5)$$

$$a_4 = \begin{cases} 1 & \text{for collinear waves and currents} \\ \frac{U_r}{6.4} & \text{for opposing waves and currents} \end{cases} \quad (6)$$

$$U_r = \text{Ursell Number} = \frac{L^2 \cdot H_{m0}}{d} \quad (7)$$

being L the wavelength and H_{m0} the spectral significant wave height.

The results of the equation can be divided and classified into three different levels of damage:

- **Static behaviour:** $S_{3D} < 0.25$.
- **Dynamic behaviour:** $0.25 \leq S_{3D} \leq 1.00$.
- **Failure:** $S_{3D} > 1.00$.

Compared with the static design, the dynamic methodology can provide scour protection with a smaller D_{n50} or D_{50} and thickness (t_s), as shown in Table 1, thereby leading to lower material, transportation, and installation costs (Matutano *et al.*, 2013). An excessive reduction of the stone size can also lead to thicker armour layers to sustain damage without failure. Therefore, a balanced solution is necessary for effective optimisation.

Table 1 – Comparison of D_{50} for different design approaches for the same tested conditions: $d=20$ m; $H_{m0}=6.5$ m; $T_p=11.2$ s; $U_c=1.5$ m/s; $D_{85}/D_{15}=2.5$ (prototype values) – adapted from De Vos *et al.* (2011, 2012).

Static Design		D_{50} (m) - prototype		Dynamic Design	D_{50} (m) - prototype	
Amplification Factor (α)	Fredsoe and Deigaard (1992) (τ_m)	Soulsby (1997) (τ_{max})	De Vos <i>et al.</i> (2011) (Eq. 1)	S_{3D} (Eq. 4)	De Vos <i>et al.</i> (2012) (Wave-current direction: 0°)	De Vos <i>et al.</i> (2012) (Wave-current direction: 0°)
2	0.68	0.66	0.50	0.2	0.44	0.46
3	1.30	1.51		0.5	0.32	0.36
4	1.97	2.75		1	0.27	0.28

Nonetheless, De Schoesitter *et al.* (2014), Whitehouse *et al.* (2014), and Fazeres-Ferradosa *et al.* (2018) extended the testing conditions of the formula, concluding that the limits established for the stability showed that some overlapping situations arose, thus the failure condition could occur for values above the limit of 1.00. Moreover, the development of this methodology, like the static protections, considered only monopile foundations and a limited range of water depths and layer thicknesses.

Recently, Broekema *et al.* (2024) performed an extensive database of 380 tests and claimed that the spatial deformation due to scour around a monopile is not unambiguous and that the classification and interpretation of scour protection's behaviour into classes is not straightforward. It requires the precise definition of what constitutes failure, which can often be “case-specific”. It highlights that calculating the scour deformation depth could be more intuitive for design purposes. It points out that, with only two parameters, it can quantitatively describe the relative scour depth (S/D) of a rip-rap protection and presents a formula to predict it – Equation (8). These two parameters and their interpretable physical meaning are:

- **MOB_{top} (Relative Mobility):** measures the hydraulic loading at the top of the scour protection relative to the resistance of the armour layer material. In practical terms, this is the stab parameter presented in Equation (3).
- **KC_{tot} (Total Keulegan–Carpenter number):** measures and evaluates the contribution of the wave-orbital and steady-current velocities relative to the structure. It measures the wave-stroke asymmetry and the difference in bed shear stress amplification around the pile.

$$\frac{S}{D} = \left[1 + \frac{3.93}{1 + \exp[-0.74KC_{tot} + 4.75]} \right] \cdot 0.07 \cdot MOB_{top}^{1.65} \quad (8)$$

Equation (8) only considers two parameters to prevent overfitting. According to Broekema *et al.* (2024), the impact of material grading width, storm duration, the ratio of water depth to pile diameter, the wave–current velocity ratio, and many others was assessed. However, none seemed to depend on the deformation, such as MOB_{top} and KC_{tot} . Moreover, the results showed a weakly positive correlation between the two parameters, *i.e.*, lower mobility numbers (relatively stable rocks) are associated with lower KC_{top} numbers (relatively large piles).

To measure deformations and identify damage areas, a moving-disk filter algorithm by van Steijn *et al.* (2023) was used, which separates scour deformation from sinking or sliding. However, the algorithm used a sub-area (A_{sub}) of $20D_{50}^2$, an area equivalent to a circle with a diameter of $5D_{50}$. Broekema *et al.* (2024) state that the selected sub-area failed to detect point deformation caused by the displacement of the larger armour layer material, claiming that the failure criterion suggested by den Boon *et al.* (2004) does not eliminate spot deformation. By averaging a local spot deformation within a sub-area of $4D_{n50}^2$ over a circular area of $4D_{50}^2$, it only represents approximately a weight of 20% within the moving average area – the local deformation is not neglected but instead weighted differently. Based on the average damage pattern from the experimental tests, Broekema *et al.* (2024) observed that scour deformations occur in three distinct areas (upstream side of the pile, deposition area, and downstream side of the pile), accordingly to the respective values of the MOB_{top} and KC_{tot} , which can be correlated to six different deformation pattern classes defined by van Steijn *et al.* (2023):

- **Class 1:** negligible deformation, small settlements, spot deformation, or slight local sinking ($1.5 \lesssim KC_{tot} \lesssim 4$ and $0.20 \lesssim MOB_{top} \lesssim 0.50$).
- **Class 2:** upstream deformation with negligible downstream deformation, associated with downflow pattern ($1.75 \lesssim KC_{tot} \lesssim 5$ and $0.20 \lesssim MOB_{top} \lesssim 0.85$).
- **Class 3:** evenly distributed upstream and downstream deformation. Increasing influence of lee-wake vortices ($2 \lesssim KC_{tot} \lesssim 5.5$ and $0.35 \lesssim MOB_{top} \lesssim 0.85$).
- **Class 4:** mainly downstream deformation. Higher prevalence of lee–wake vortices ($3.5 \lesssim KC_{tot} \lesssim 8$ and $0.40 \lesssim MOB_{top} \lesssim 1.10$).

- **Class 5:** deep upstream deformation combined with a single deep downstream deformation point. It can be difficult to distinguish from Class 4 but is highly related to the presence of a meaningful steady current ($2.5 \lesssim KC_{tot} \lesssim 9.5$ and $0.35 \lesssim MOB_{top} \lesssim 0.95$).
- **Class 6:** deformation mainly upstream with a single relatively shallow downstream deformation point. Associated with low current velocities or even only-wave conditions. Horseshoe vortices prevail over lee–wake vortices ($3.5 \lesssim KC_{tot} \lesssim 5$ and $0.6 \lesssim MOB_{top} \lesssim 0.8$).

By comparing tests with similar KC_{tot} and MOB_{top} but with different wave and current contributions (only-waves, wave-dominant, and current-dominant conditions), it was observed that the predicted scour depth was of the same order of magnitude as the measured values. Equation (8) showed a correlation coefficient of 0.85 between measured and predicted S/D values (Broekema *et al.*, 2024). Nonetheless, it was noted that the formula can sometimes overestimate and underestimate S/D for smaller or larger KC_{tot} , respectively. Additionally, the deformation and scour patterns observed were significantly different, and in some cases, the classes were difficult to distinguish because the values for both parameters overlapped within each deformation class. This observation was partially attributed to the orbital wave motion's asymmetry at higher current velocities. It emphasises that combining the hydrodynamic conditions is important to determine where the peak deformation will occur. In contrast, the values of the KC_{tot} and MOB_{top} parameters will predict the possible range of scour depth and damage. Broekema *et al.* (2024) highlights the need to develop a design formula combining scour depth, area, and volume, with guidelines on the volume–area–depth relation and requirements for a universal, clear, and unambiguous definition of scour protection failure.

Hence, the application of dynamic scour protections to complex foundations and for a wide variety of hydrodynamic and structural conditions remains a knowledge gap yet to be addressed in the literature.

2.3.3. WIDE-GRADED PROTECTIONS

Single-layer protections formed by wide-graded material that simultaneously behave as an armour and filter layer have been identified in the aftermath of several studies performed by De Vos *et al.* (2011), Schendel *et al.* (2014), Schendel *et al.* (2016), Schendel (2018), and Schendel *et al.* (2018) to optimise scour protections. Compared with narrow-graded scour protections, an overall increase in stability was achieved by sheltering smaller stones within the voids of larger stones and by reducing the washout of finer particles (De Vos *et al.*, 2011; Schendel *et al.*, 2014).

For wide-graded protection, De Vos *et al.* (2011) proposed the following design formula,

$$\tau_{cr} = \theta_{cr} \cdot g \cdot (\rho_s - \rho_w) \cdot D_{67.5} \quad (9)$$

where $D_{67.5}$ and $\theta_{cr}=0.035$ are used instead of D_{50} and $\theta_{cr}=0.056$, so τ_{cr} can be significantly higher for the same D_{50} value, accounting for the sheltering effect.

From the perspectives of stability, material availability, installation, and cost, wide-graded protections are quite appealing. However, for dynamic wide-graded protections, the literature indicates that Equations 3 and 4 do not apply, as they are based on a filter exposure that does not exist in wide-graded protection and are applicable to both monopiles and complex foundations. Moreover, there is a lack of reported experimental data, tests, and results, as well as in-field applications. Therefore, this type of protection remains a concept whose efficiency is not yet fully developed or understood.

In the end, scour protection optimisation studies are still crucial, particularly for complex or hybrid structures, for which, to the author's knowledge, no studies are available. It is necessary to determine whether the existing design formulas for monopiles are transferable and viable for other types of offshore foundations, or whether improvements are needed to enhance cost reductions or improve savings of different *in situ* solutions compared to the static protection concept.

2.4. COMPLEX FOUNDATIONS

Research on marine renewable energy has recently focused on the potential for co-located harvesting technologies, which necessitates the creation of hybrid structures, or foundations (bottom-fixed or FOWT) that can accommodate multiple technologies. Hybrid structures represent a study area with expanding potential, given the possibility of risk and investment sharing among concurrently utilised technologies. Co-locating OWTs, WECs, TECs, and other technologies often requires the use of offshore foundations with complex geometries that exhibit scour behaviour distinct from that of monopiles (Fazeres-Ferradosa *et al.*, 2021).

In recent years, there has been an increased discussion about scour on complex foundations (Fazeres-Ferradosa *et al.*, 2021). However, scour protection for these types of foundations has not yet been thoroughly addressed. The application of energy converters can exacerbate or mitigate scour-related problems, such as instability, fatigue, or differential settlements, thereby affecting the protection behaviour.

The scour prediction and design formulas that are currently in use, along with other scour countermeasures, were primarily created for monopiles. However, for complex foundations, these approaches are often conservative, and some methodologies do not immediately translate, as they do not account for foundations' various geometries or the increased importance of local scour (Fazeres-Ferradosa *et al.*, 2021).

To better understand the scouring process and its structural influence on scour behaviour, and to develop appropriate protective measures for complex foundations, the following sub-chapters will present some of the findings reported by various authors in recent studies.

2.4.1. JACKET FOUNDATIONS

Structure assembled with steel tubular elements, suited for intermediate waters, jacket foundations are heavily used on offshore oil and gas platforms. It is the second most common foundation type used for offshore wind turbines (Figure 2) and the most popular among complex foundations (WindEurope, 2021b).

The different structural configurations of a jacket, combined with other elements such as diagonal bracings, horizontal elements, and J-tubes, create a blockage effect that alters hydrodynamic conditions. This leads to flow contraction, increased current velocities, lee-side vortices, turbulence, and changes in sediment transport gradients, thereby enhancing scour in the vicinity of the structure (Fazeres-Ferradosa *et al.*, 2021). Some structural characteristics, such as tube diameter, joint and brace angles, and distance between braces, can magnify or diminish this blockage effect (Welzel *et al.*, 2019a). A comparison of scour depth between two jackets with different distances from the lowest node to the seabed and from the diagonal braces to the seabed is validated by Welzel *et al.* (2020). This study also concluded that even a slight change in the distance of the lowest node can have a significant impact on scour. Specifically, lower node and diagonal brace distances to the seabed lead to deeper local erosion in the

vicinity of the piles and increased erosion around the footprint area in a current-dominated regime. However, there is less global scour in conditions where waves prevail.

When some *in situ* scour depths were compared with predicted values from monopile design formulas (Bolle *et al.*, 2012; Welzel *et al.*, 2019a), a discrepancy was observed. In fact, field-scour depths can reach considerably higher values (Bolle *et al.*, 2012). This reinforces the idea that more studies are still necessary to develop more accurate predictive formulas (Fazeres-Ferradosa *et al.*, 2021).

Novel empirical expressions, Equation (10a), account for the influence that the distance of both the node and the inferior diagonal brace nearest to the seabed can have on scour (Welzel *et al.*, 2020). Where coefficient B is included to distinguish the impact of the distance to the seabed of the lowest node (Figure 4), and parameter A differentiates the upstream (A_{front}) and the downstream (A_{rear}) sides of the structure. It is also equal to the reference distance multiplied by the structure footprint length (Figure 5). Specifically, to estimate scour at the footprint, $1.0A$ should be used; to estimate scour at an area of influence equal to twice the footprint, $2.0A$ should be used, and so on.

As shown in Table 2, the S/D values tend to be higher for pile 1 (pile further ahead facing both waves and currents) than pile 3 (pile further back facing both waves and currents), due to the shadow effect, indicating that the most exposed pile to hydrodynamic conditions has the most necessity to be protected. It also suggests that the relative scour depth tends to increase with higher U_{cw} , for a given KC (Keulegan-Carpenter number), indicating that scour aggravates under higher hydrodynamic conditions, particularly in current-dominated conditions ($U_{cw} \geq 0.5$).

$$\frac{S}{D} = (0.7 + \exp(-6.5U_{cw}^{2.5} - A))^{1.5} + B \quad (10a)$$

$$A_{front} = 1.66KC^{0.34} - 4.5 \quad (10b)$$

$$A_{rear} = 1.30KC^{0.40} - 4.6 \quad (10c)$$

$$B = \begin{cases} 0.17, & \text{node distance} = 0D \\ 0.22, & \text{node distance} = 1D \end{cases} \quad (10d)$$

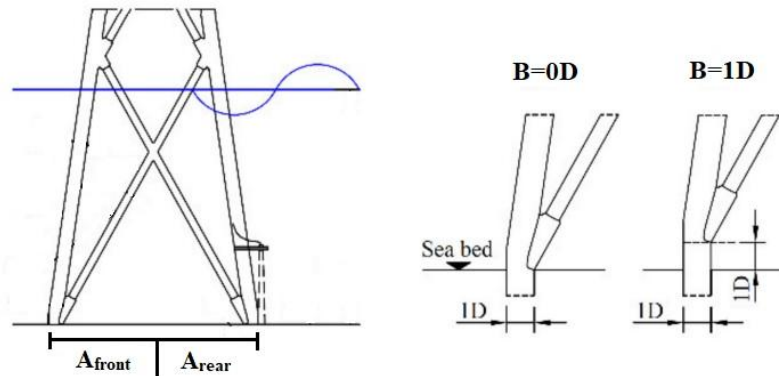


Figure 4 - Visual representation of the parameters A and B (adapted from Welzel *et al.*, 2020).

Additionally, new volume analysis methods, along with dimensionless parameters, were introduced, which can be adapted for offshore complex foundations (Welzel *et al.*, 2019b). It also includes the

derivation of equations to predict maximum erosion volumes, Equation (11), and cumulative erosion volume, Equation (12a), over a certain distance A from the centre of the structure. The tests revealed that the area of the seabed affected by the structure is considerably larger (between 2.1 and 2.7 times the structure's footprint), where the maximum erosion intensity appears to be found in the vicinity of an area equal to 1.25 times the structure's footprint area.

Global and local scour give different indications of scour patterns around the structure. Local scour indicates that scour holes develop primarily around the foundation piles, whereas global scour indicates that the scour rate and depth are extended around the entire jacket foundation (Welzel *et al.*, 2019b). A comparison between local and global erosion volumes revealed that, for wave-dominated conditions, scour depth and patterns are dominated by local scour (68%). In contrast, in current-dominated conditions, global eroded volume rates were higher (67%) for $U_{cw} \geq 0.75$ (Welzel *et al.*, 2019b). These values indicate that for zones where waves dominate hydrodynamic conditions, scour protections should be designed only for each pile or reinforced with a higher thickness near the piles, whereas for current-dominated zones, scour protections should be reinforced near the piles but also designed for a much greater extent, to cover the structure's footprint area and the surroundings.

Although neither study considers scour protections, they could help inform their development. They provide valuable information on scour patterns (Figure 6), scour depth (Table 2), and erosion volumes, indicating the extent, thickness, and where to reinforce the scour protection. Moreover, the results, when compared with *in situ* data (Baelus *et al.*, 2018; Bolle *et al.*, 2012; Rudolph *et al.*, 2004), showed good correspondence (Welzel *et al.*, 2019b).

Some numerical models were also applied to compare predictive values with *in situ* measurements. Numerical simulations of the C-power wind farm at Thornton Bank, under current and wave conditions, were carried out to predict local scour (Ahmad *et al.*, 2020). The results of maximum scour agreed well with the reports for a 4-pile jacket foundation (Bolle *et al.*, 2012). A numerical model of a multi-bucket jacket foundation, which suggested a scour prediction formula for currents based on dimensionless parameters for a specific range of values (Table 3), was also developed (Lian *et al.*, 2022).

$$V_{A,max} = -1.3(0.1 + \exp(-4.6U_{cw}))^{1.5} \quad (11)$$

$$V_{A,i} = V_{Area} - 1.3(0.1 + \exp(-4.6U_{cw}))^{1.5} \quad (12a)$$

With

$$V_{Area} = \begin{cases} ((0.1 + \exp(-10A + 8))^{-0.9} \cdot B' - C', & A < 1.25A \\ -2.2 \exp(-0.7A) - 0.11, & A > 1.25A \end{cases} \quad (12b)$$

$$B' = (-5.2U_{cw} + 6.9) \cdot 10^{-2} \quad (12c)$$

$$C' = (3.8U_{cw} + 4.9) \cdot 10^{-1} \quad (12d)$$

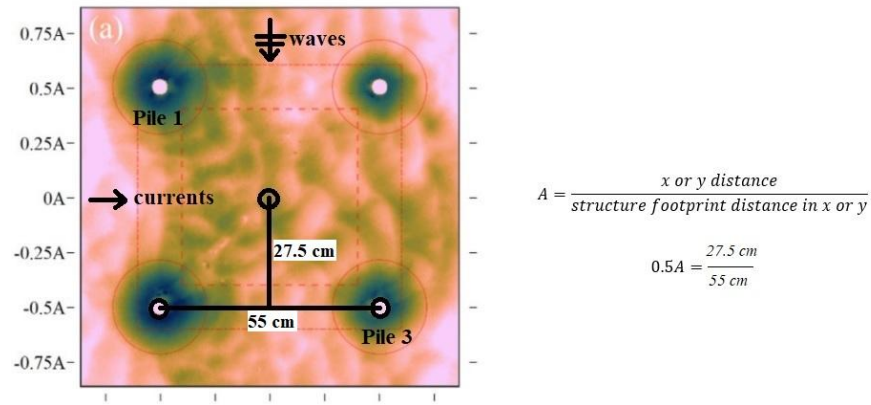


Figure 5 - Surface elevation of a scour test (blue and green: scour), and representation of dimensionless parameter A (adapted from Welzel *et al.*, 2020).

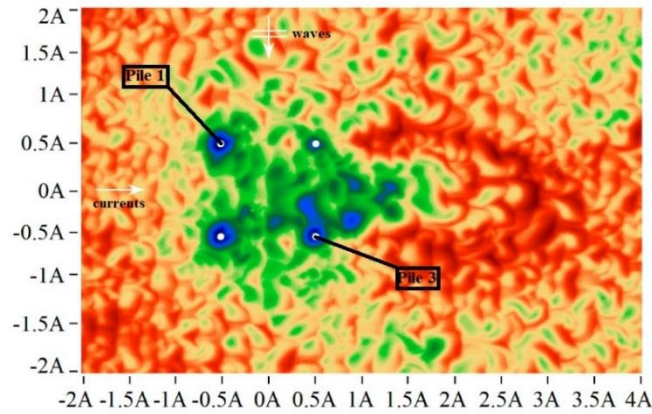


Figure 6 - Bed topography - blue: local scour, green: global scour, red: depositions (adapted from Welzel *et al.*, 2019b).

Table 2 - Test results and conditions for jackets scour tests (Welzel *et al.*, 2020) - prototype values.

Test	Node Distance (m)	H_s (m)	T_p (s)	U_m (m/s)	U_c (m/s)	U_{cw} (-)	Current-Wave direction	KC (-)	S/D_{pile1} (front)	S/D_{pile3} (rear)
1	0D	4.41	10.95	0.73	0.55	0.43	90°	6.7	0.403	0.238
2					1.23	0.63			0.801	0.786
3					2.13	0.75			1.571	1.268
4					0.55	0.37			0.884	0.580
5					1.23	0.56			1.317	1.075
1	1D	4.41	10.95	0.73	0.55	0.43	90°	6.7	0.464	0.271
2					1.23	0.63			0.863	0.708
3					2.13	0.75			1.502	1.133
4					0.55	0.37			0.735	0.622
5					1.23	0.56			1.205	1.038

Few recent works have tested scour protections for jacket foundations. An extensive review of those works can be found in Fazerer-Ferradosa *et al.* (2021). Table 4 provides a brief overview of selected physical model test results. The main conclusions of those studies are as follows:

- An East Anglia One offshore wind farm 3-legged jacket foundation model (Figure 7), with front mats and high-density rip rap scour protections, has been tested for three cumulative sequential tests of waves and currents (ascending, descending, and random), Sarmiento *et al.* (2021). The erosion patterns were similar across all test sets. It was concluded that a decreasing sea-state sequence leads to greater erosion and cumulative damage than an increasing or random sequence. For the most exposed jacket leg, the maximum scour depth of $5D_{50}$ was recorded for the descending sequence. As for the ascending and random sequences, the maximum scour depth was $3D_{50}$. The least-exposed jacket leg registered a maximum scour depth of $2D_{50}$ for the least-favourable sequence of tests. Regarding scour extent, the worst case was also observed for the descending sequence, compared to the ascending or random sequence (approximately $0.5D$ from the edge of the jacket leg).
- Jacket foundation models of the HZK Offshore Wind Farm and the Borssele Wind Farm and OHVS (Figure 8), respectively, with different displacements of the material of the scour protection have been tested (Bruinsma *et al.*, 2018; Van Velzen and Bruinsma, 2017; Van Velzen *et al.*, 2016). Three different configurations of the scour protection were studied: a single-layer system with a post-installed jacket and a two-layer system with both post- and pre-installed jackets. Results showed some similarities between the two studies, and it was concluded that scour protection remained relatively stable regardless of whether it was applied before or after the jacket was installed. The two-layer system, with the armour layer installed after the jacket's installation, was deemed the worst option for the armour layer's stability. The study also highlights the importance of the filter layer in a two-layer protection system.
- A 4-layer scour protection around a jacket foundation model for waves and currents (Figure 9), as well as an alternative, soft scour countermeasure, *i.e.*, coastal cage net for aquaculture, was tested (Hsin-Hung *et al.*, 2014). Both solutions proved effective, reducing the scour depth. Moreover, the integration of a coastal cage net demonstrates that it can be a meaningful and helpful measure in preventing scour around offshore foundations.



Figure 7 - Scour protection for a model of the East Anglia One 3-leg jacket (Sarmiento *et al.*, 2021).

Table 3 – Numerical model conditions used by Lian *et al.* (2022).

Reference	Lian <i>et al.</i> (2022)
d (m)	40
U_c (m/s)	1
U_{max} vortices (m/s)	[1.35 – 2.76]
Calculation time (s)	3600
Output time (s)	300
Bucket Diameter (m)	[10 - 30]
Bucket Spacing (m)	[30 - 50]
Bucket Exposed Height (m)	[0 - 3]
Hydrodynamic Load	Currents only

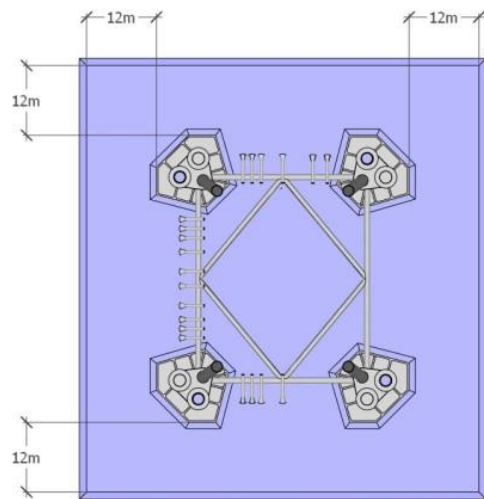
**Figure 8** – Scour protection layout for a 4-leg jacket model of the Borssele Offshore High Voltage Station (Bruinsma *et al.*, 2018).**Figure 9** - Scour protection model for a 4-leg jacket (Hsin-Hung *et al.*, 2014).

Table 4 - Studies related to jackets' scour protections – prototype values.

Reference	Sarmiento <i>et al.</i> (2021)	Bruinsma <i>et al.</i> (2018)	Hsin-Hung <i>et al.</i> (2014)
Scale	1:30	<i>In situ</i>	1:36
d (m)	39.93	[30.00, 32.30]	[12.00, 16.00]
T_p (s)	Not provided	[0.00, 12.50]	[7.00 - 11.74]
U_c (m/s)	50-year Return Period (exact value not provided)	[0.00, 1.20]	[0.00, 1.00]
Types of Waves	Irregular	Irregular	Irregular
H_s (m)	[1 – 50] year Return Period (exact value not provided)	[0.00, 8.90]	[2.50 - 7.72]
Duration	3 h (18h cumulative)	Not provided	8h
Wave-current direction	0°	Not provided	90°
D (m)	Not provided	Not provided	4-pile jacket (2.08 m diameter /pile)
Protection type	Rip-rap	Rip-rap	Rip-rap + Precast concrete blocks
D_{n50} (mm)	Not provided	[76.2 – 228.6]	Not provided
ρ_s (kg/m ³)	Not provided	3050	Not provided
Armour Thickness	Variable (but up to 5D ₅₀)	1 m	3 m (2 m embedded in the seabed)
Armour Extent	Not provided	12 m radius from each pile (square protection)	14 m radius from each pile (square protection)
Filter	-	-	Geotextile and Granular

While there is an apparent lack of studies on scour protections applied to jackets, in recent years, the number of scour model tests performed on jackets has been increasing for both physical models (Hsin-Hung *et al.*, 2014; Welzel *et al.*, 2020; Welzel *et al.*, 2019a; Welzel *et al.*, 2019b) and numerical models (Ahmad *et al.*, 2020; Lian *et al.*, 2022). These studies aimed to cover important scour parameters, including the S/D ratio, the scour width, the dimensionless time scale (T^*), the equilibrium scour depth (S_{eq}), eroded volumes and areas, and scour estimates for regimes dominated by currents, waves, or equally by both. One reason may be the growing interest in reusing existing platforms for OWT installations, as well as the use of jackets for offshore high-voltage stations. In addition, there has been an increased effort to develop scour design equations, as monopile formulas inaccurately predict scour for complex structures. Moreover, new findings can serve as a basis for further studies to develop novel design formulas for scour protection.

2.4.2. TRIPOD FOUNDATIONS

Tripods are complex structures composed of three piles connected to the central column by diagonal braces, best suited for intermediate waters. Studies involving scour protection for this type of complex structure are rare. The scour process and its development for tripods differ significantly from those for monopiles or pile groups.

Tests with tripods, hexapods, a triangular array of circular cylinders (TACC), and a hexagonal array of circular cylinders (HACC) have been performed under current conditions and compared with monopiles (Ni and Xue, 2020). The work shows that the relative maximum scour depth (S_{max}/D) is approximately 30% higher for tripods and hexapods than for TACCs and HACCs, respectively, indicating that the lower diagonal braces of the complex structure create blockage effects that enhance scour.

A setup of physical and numerical model tests to assess scour on tripods under regular waves (scale: 1:40, $H=8.25$ m, $T_m=19$ s, and $d=30$ m – prototype values) was performed for a 4000-wave cycle (Stahlmann, 2014). Scour was observed under the central column, in the vicinity of the lower braces connecting the piles to the columns, and at the front/rear piles. For the physical model, the rear piles registered the highest relative scour depth ($S/D = 0.85$). As for the front pile, the S/D decreased to 0.59, and under the central column, the relative scour depth was equal to 0.44. The values recorded in the central column can be explained by the blockage effects described by Ni and Xue (2020) for the lower braces. Scour depths reached an almost equilibrium stage after 3000 waves, with 90% of the corresponding values achieved after 1500 waves. The scour patterns identified were similar to those reported by other researchers (Harris and Whitehouse, 2014; Stahlmann and Schlurmann, 2010). Regarding the numerical model, the scour depths for the front pile were in good agreement with the experimental results. However, scour depths at the rear pile and under the central column were about 20% lower and 32% higher, respectively. This difference had no clear explanation, and it was assumed to be related to hydrodynamic processes and wave absorption procedures.

The research comparison between *in situ* data, large-scale (1:12) and small-scale (1:40) tests performed by Stahlmann and Schlurmann (2010) for the Alpha Ventus Offshore wind farm allows for similar conclusions to be drawn from Stahlmann (2014). The tests were performed for regular and irregular wave cycles at different incoming wave angles: 0° (one pile facing the waves), 30° (an asymmetric constellation), and 60° (two piles facing the waves). Table 5 provides a brief overview of the setup conditions, some of the S/D values obtained for the 0° configuration under regular waves with maximum wave height and period, and the *in situ* measurements.

Overall, both the large- and small-scale tests showed that global scour (highly related to scour extent) and local scour (highly associated with scour depth) were strongly dependent on wave direction. Comparing the results of the two scale tests, it was notable that the 1:12 tests yielded S/D values for the structural elements approximately 50% higher than those from the small-scale tests. As for the near field of the structure, the difference was explained by the influence of the ripple formation. The large-scale tests also showed that regular wave conditions, with wave heights and periods like those of irregular waves, led to higher sediment mobility around the structure, thereby increasing global scour, despite local scour at the piles and under the central column reaching similar values (Stahlmann and Schlurmann, 2010). Regarding *in situ* measurements, when compared directly with the large-scale tests, the measured S/D values were higher, particularly under the central column. These differences were attributed to the tested model wave conditions (real sea state conditions and wave directions were simplified), scale effects of the sediments (not correctly scaled to maintain non-cohesive properties), and mainly the fact that only waves were used, instead of real wave-currents offshore conditions

(Stahlmann and Schlurmann, 2010). However, both models showed good agreement with the *in situ* measurements regarding the development and extent of local and global scour – maximum scour depths and shapes occur at similar locations.

Table 5 – Physical models and *in situ* scour analysis for tripods – prototype values.

Reference	Stahlmann and Schlurmann (2010) and Stahlmann (2014)		
Scale	1:40	1:12	1:1
d (m)	[24, 30]	30	28
T_p (s)	[9.5 – 19.0]	[9.6 – 19.1]	<i>In situ</i> Conditions (50-year period): Waves: $H_{s,50}=8.5$ m, $H_{max,50}=15.8$ m, $T_{p,50}=12.3$ s Currents: $U_{c,50}=1.3$ m/s, $U_{c,ground50}=0.8$ m/s
Types of Waves	Regular+Irregular	Regular+Irregular	
H_s (m)	[4 – 12]	[6.12 – 9.24]	
Duration	[3000 - 6000] waves	[2500, 3000, 4000] waves	
D (m)	Not provided	Not provided	
S/D (Rear pile 1)	0.66	1.05	[1.1 – 1.4]
S/D (Rear pile 2)	0.67	1.03	
S/D (Front pile)	0.55	0.80	
S/D (under the central column)	-	1.11	2.5
S/D (downstream)	0.92	0.31	-

For tests under currents and waves, a tripod with three different orientations was studied (Hu *et al.*, 2021), according to the position of the wave-current direction: (i) 0° – a pile facing the wave-current direction; (ii) 90° – asymmetric, with the wave-current direction being perpendicular to a brace; and (iii) 180° – two piles facing the wave-current direction. The maximum scour occurs beneath the central column, while the scour patterns extend into the area of the inferior diagonal braces. The blockage effect explains these characteristics by increasing shear stress on the seabed through streamlined contraction (Hu *et al.*, 2021). However, results also showed that for the 90° orientation, a higher S/D value was reached. The following main conclusions could be addressed (Hu *et al.*, 2021):

- Diagonal braces facing waves and currents increase the blockage effect.
- When currents are superimposed, the dimensionless time scale for a 90° orientation increases, thus the equilibrium states are achieved for a longer time scale.
- The comparison of experimental data with predicted values of the equilibrium scour depth formula (Sumer and Fredsøe, 2002) revealed that the former returned 25% higher scour values for a 90° orientation, thus recommending the use of a safety coefficient of 1.3.

The results indicate that some current methodologies may be adapted to predict scour and to potentially design scour protection for tripods (Hu *et al.*, 2021). It also recommends that scour protections around tripods should be thicker than those around monopiles and reinforced in critical areas, such as under the central column and diagonal braces.

A numerical model for random waves was performed (Hu *et al.*, 2022) and compared with other experimental investigations (Schendel *et al.*, 2020; Sumer and Fredsøe, 2001). The model demonstrated the ability to predict both equilibrium and maximum scour depths with relatively satisfactory accuracy. The maximum error between the numerical results and experimental values (Schendel *et al.*, 2020; Sumer and Fredsøe, 2001) was less than 30% in most cases. Moreover, all scour patterns (Hu *et al.*, 2022) were similar and aligned with results from several studies (Stahlmann, 2013, 2014; Stahlmann and Schlurmann, 2010).

It is evident that the literature remains insufficient and addresses only scour depths and inherent patterns. The authors were unable to find studies regarding scour protections for offshore wind tripod foundations. Nevertheless, the information provided about local and global scour development lays a foundation for future studies of scour protection's damage and protection design, since, like other complex foundations, tripods differ considerably from monopiles in terms of scour behaviour.

2.4.3. GRAVITY-BASED FOUNDATIONS (GBFs)

Gravity-based foundations are heavy concrete structures, suited for shallow waters, and are designed so that their self-weight withstands high overturning moments. Scour and scour protections on GBFs are less studied than in jackets or monopile foundations. Most studies are conducted by private companies, which generally do not provide sufficient data to the public due to the sector's restrictive confidentiality policies (Fazeres-Ferradosa *et al.*, 2019b).

Guidelines for scour management plans, along with a review of scour and protections, emphasise that in non-cylindrical GBFs, certain areas are more susceptible to scour due to blockage effects around their edges (Whitehouse *et al.*, 2011b). These observations were also reported in a model of a STRABAG foundation – a reinforced, sand-filled concrete foundation with a cross-shaped base – that underwent physical and numerical studies (Wilms *et al.*, 2012). As scour protection, a two-layered sand-filled geotextile was used instead of a rubble-mound armour layer (Figure 10).



Figure 10 – Scour protection model of a STRABAG foundation using geotextile containers (Wilms *et al.*, 2012).

Scour tests performed by Wilms *et al.* (2012) in a large physical model at a scale of 1:17 revealed that the zones most prone to scour are at the front and rear shafts, bracings, and lee corners of the hollow boxes. It was concluded that sand containers provided hydraulically stable scour protection. The numerical model demonstrated that the foundation's cross-shaped configuration increased the flow field

and velocities due to the blockage effect, thereby enhancing the scour process (Wilms *et al.*, 2012). The manuscript also includes a brief analysis and comparison of the S/D for non-protection and protection scenarios, revealing that overall scour development was high between 500 and 1000 waves, then decreased slightly at 2000 waves. In cases where protection was used, scour depths and widths were smaller. A significant difference in the results was observed at 5000 waves, where the S/D value was almost half that obtained in the model without protection. Given the use of geotextile containers for scour protection, their dynamic behaviour was not examined.

De Sonnevile *et al.* (2014a) studied the application of dynamic scour protection to a gravity foundation to investigate scour around a DolWin Beta offshore converter model. The scour protection applied around the rectangular foundation did not have a uniform thickness, as a different methodology was used: reinforcement of critical areas and a smaller thickness in sheltered zones. Dynamic stability was observed under the conditions used, even for only 2000 waves. It was concluded that high-density stones can be used for optimisation, as enhanced stability was achieved through reductions in volume and rock size. It also determined that currents are paramount in scour, even in a wave-dominant regime.

Chen *et al.* (2011) tested a dynamic scour protection physical model for the Adriatic Liquefied Natural Gas (LNG) terminal (Figure 11). The structure was composed of a gravity-based structure (GBS) and two mooring dolphins. The objective was to determine the maximum scour depth, assess if a filter layer was necessary, and evaluate the edge scour of the protection. For a 1:50 scale, four scour protection layouts were submitted for wave and current conditions (Table 6) at a 100-year return period from the project site, considering Bora winds (resulting in waves from North-East to East) and Scirocco winds (resulting in waves from South-East).

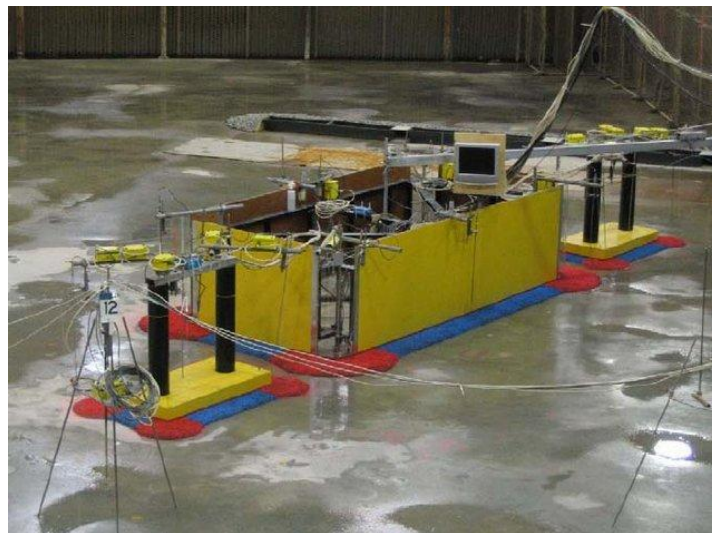


Figure 11 - Scour protection of the Adriatica LNG terminal and mooring dolphins (Chen *et al.*, 2011).

The final design consisted of an armour layer with varying thickness and width, but without a filter layer. The study concluded that the scour protection sustained limited damage and that the optimised layout version increased the protection thickness at the mooring dolphins and decreased the width around the main structure. The results indicate that the sharp corners of the mooring dolphins lead to

significant erosion. At the main structure, scour was also more severe in the corners than around the structure's edges.

Gao *et al.* (2023) conducted experimental research on a 1:100 geometrically scaled GBS, composed of two pontoons, six supporting columns, and cross braces. The model was tested under conditions of currents only and waves only (Table 6) at two angles (0° and 90°) by rotating the platform (Figure 12). The novelty of this study lay in the implementation and comparison of seven different scenarios (six different scour protection systems): no protection, geotextile, riprap, geotextile-riprap, bionic grass, bionic grass-geotextile, and bionic grass-geotextile-riprap (Figure 13). Scour measurements were made from three-dimensional bed topographies obtained with a laser scanner. It was concluded that when the highest U_c value was applied with a 90° direction, led to the inclination and collapse of the platform; the maximum scour depth was registered for the 90° current-only conditions ($S_{max}/D=1.12$) when compared to the 90° waves-only conditions ($S_{max}/D=0.193$); and by comparing the different scour protection methods for the worst scenario (currents-only), it was concluded that the bionic grass, the bionic grass-geotextile, and the bionic grass-geotextile-riprap systems presented the best protection efficiency by reducing scour in orders of 68.7% (0° direction) and of 80.1% (90° direction) – Figure 14.

As a side note, this study performed by Gao *et al.* (2023), also shows that for “usual” scour protection systems that are applied in physical model tests (riprap or geotextile-riprap), the riprap protection as an efficiency of 7.0% and 55.6%, for 0° and 90° degrees respectively, and the geotextile-riprap has shown an efficiency of 44.4% and 49.8%, for 0° and 90° degrees respectively. These values demonstrate that a geotextile-riprap system exhibits more consistent performance across multiple directions of hydrodynamic conditions, with a surplus of 37.4% for the 0° direction (although it performs slightly worse in the 90° direction). This answers, in part, some questions in the literature regarding the best material for the filter layer and the differences in performance.

In the study performed by Tavouktsoglou (2018) on GBFs and scour protections, evidence was provided that, in a wave-dominated regime, the amplification factor of the bed shear stress is smaller than 2. It also proposed an equilibrium scour depth formula (Equation 13a) for complex and simple structures, reliable for currents only but conservative for offshore conditions – where D_{base} (m) is the diameter of a non-uniform cylindrical structure, ζ is a parameter that relates the Reynolds number of the structure (Re_D), the water level (h), the Froude number (Fr), the Euler number (Eu), the U_c , the mean threshold velocity of sediments (U_{cr}) – $c1$, $c2$, $c3$ are regression fitting coefficients.

Developing a threshold-based motion design could be an alternative approach, as stated by Fazerres-Ferradosa *et al.* (2021). Table 6 summarises the physical scour protection models for GBFs reported in the literature.

$$\frac{S}{D_{base}} = \frac{c1 \cdot \zeta + c2}{\zeta + c3} \quad (13a)$$

With

$$\zeta = \frac{1}{\log(Re_D)} \cdot \frac{h}{D_{base}} \cdot Fr \cdot (Eu)^{0.5} \cdot \left(\frac{U_c}{U_{cr}}\right)^{0.5} \quad (13b)$$

$$c1 = [2.1, 2.3]; \quad c2 = [-0.009, 0.005]; \quad c3 = [0.01, 0.05] \quad (13c)$$

Although few research studies have been conducted on scour protection for GBFs, the number of works is insufficient to cover a substantial range of offshore conditions, to address or evaluate the dynamic behaviour of such protections, or to present or optimise novel design formulas for this type of foundation. Hence, this review highlights the importance of extending these testing conditions to advance the development of scour protection design methodologies for GBFs.

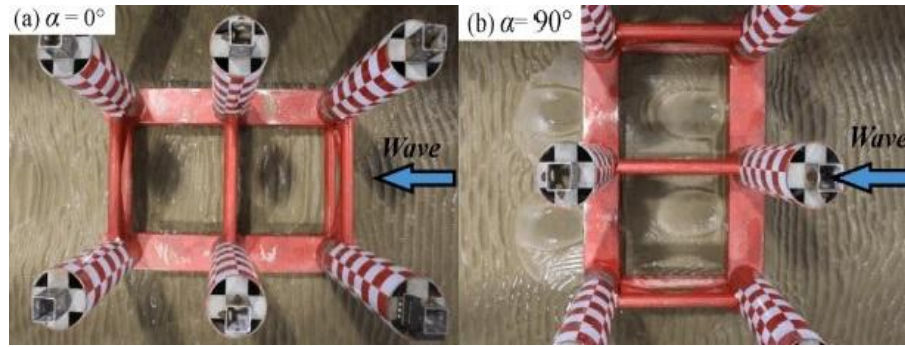


Figure 12 - GBS submitted to waves-only for 0° and 90° directions (adapted from Gao *et al.*, 2023).

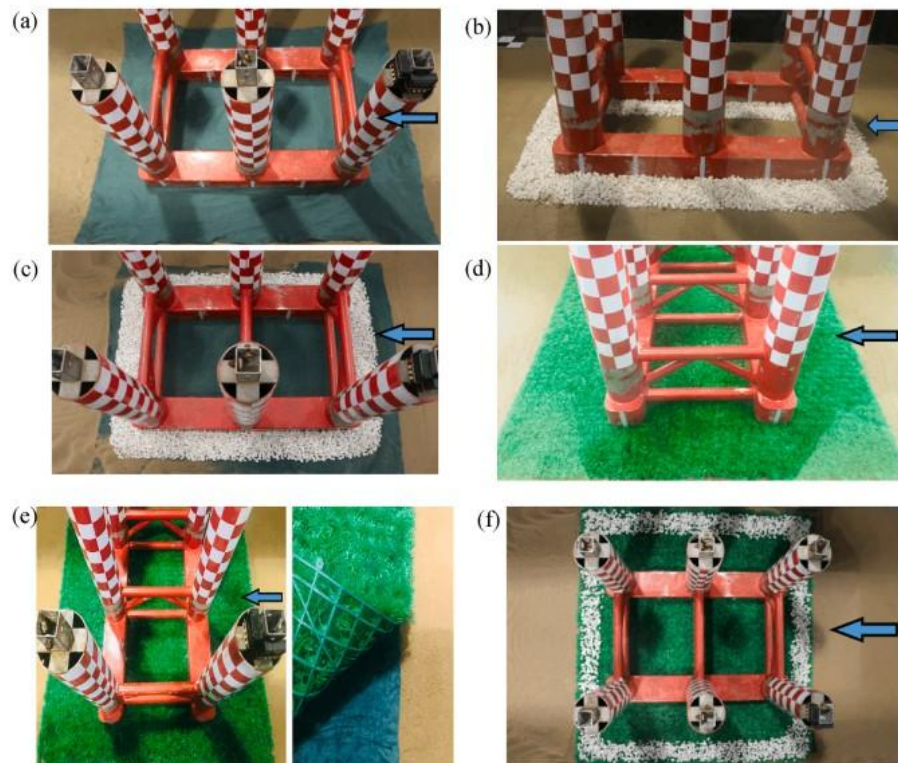


Figure 13 – Scour protection systems: (a) geotextile; (b) riprap; (c) geotextile-riprap; (d) bionic grass; (e) bionic grass-geotextile; (f) bionic grass-geotextile-riprap (Gao *et al.*, 2023).

Table 6 – Physical modelling studies for GBFs’ scour protections – prototype values.

Reference	Wilms <i>et al.</i> (2012)	De Sonnevile <i>et al.</i> (2014a)	Chen <i>et al.</i> (2011)	Gao <i>et al.</i> (2023)	Tavouktsoglou (2018)
Scale	1:17	1:60	1:50	1:100	1:100
d (m)	37.5	[28.2, 29.3]	29	30	40
T_p (s)	13.8	[0.0 – 13.6]	Bora: 9.9 Scirocco: 12.0	[8.0 – 12.0]	[10.0 – 30.0]
U_c (m/s)	-	[0.30 – 2.00]	Normal direction: Bora: 0.53 Scirocco: 0.10 Inline direction: Bora: 0.07 Scirocco: 0.18	[1.5 – 2.5]	[-2.9 – 6.5]
Types of Waves	Irregular	Irregular	Irregular	Regular	Regular
H_s (m)	10.8	[0.0 – 10.0]	Bora: 5.3 Scirocco: 5.9	[5.5 – 8.5]	[0.0 – 16.0]
Duration	5000 waves	2000 waves 15.5h (only currents)	18 h	3h	10 000 waves 5h (only currents)
Wave-current direction	-	0° Bidirectional	Bora: 60° Scirocco: 150°	Currents: [0°, 90°] Waves: [0°, 90°]	[0°, 90°]
D (m)	32.5	90 x 70 (rectangular)	Main Structure: 88 x 180 (rectangular) Mooring Dolphins: 56.4 x 28.4 (rectangular)	Main Structure: 70 x 90 (rectangular)	20
Protection type	Geotextile sand containers	Rip-rap	Rip-rap	6 different systems	Rip-rap
D_{n50} (mm)	Container: 2.05 m x 2.05 m	[250, 360, 420]	Not provided	760	[294, 546, 882]
ρ_s (kg/m ³)	Not provided	[2650, 3200]	Not provided	1700	[2500, 2550, 2620]
Armour Thickness	2 layers	$5D_{n50}$ (initial) Varying (final)	Varying	$2.5D_{50}$	Not provided
Armour Extent	52.5 m (diameter)	118 m x 98 m (initial) Varying (final)	Varying	1.25 to 1.5 D	$5D$
Filter	Not used	Granular ($D_{50}=0.05$ m)	Not used	Varying	Geotextile

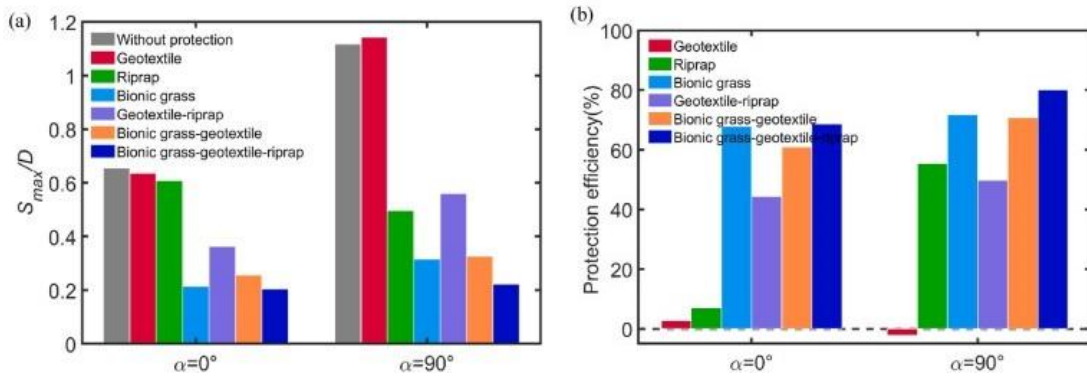


Figure 14 – S_{max}/D and Protection efficiency (%) for different scour protection systems for the maximum flow velocity ($U_c=0.25$ m/s), Gao *et al.* (2023).

2.5. MARINE ENERGY CONVERTERS AND HYBRID STRUCTURES

Nowadays, OWTs and marine harvesting technologies have seen increasing interest from the private and scientific communities in the marine renewable energy sector.

The energy crisis and climate change are increasing demand, exploration, and investment in hybrid structures that combine multiple energy-harvesting technologies, for example, offshore wind turbines with marine energy converters on the same structure or floating platform (Figure 15). These hybrid systems could optimise and boost power and energy production per structure. The question is whether energy converters can shield OWTs from waves, currents, and tides, or increase loads, turbulence, and scour mechanisms (downflow, horseshoe, and/or lee-wake vortices) around the foundation.

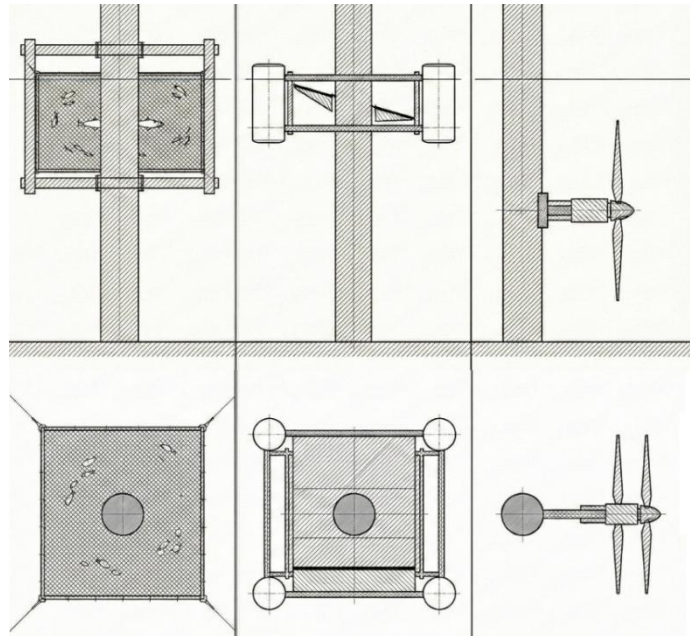


Figure 15 – Scheme of different hybrid offshore structure configurations: Monopile combined with aquaculture cage (left), oscillating wave surge converter wave energy converter (centre), and tidal/current energy converter (right).

Most of the new hybrid structures combine floating OWTs with WECs or TECs. Since this study focuses on bottom-fixed complex foundations and hybrid structures, other studies are highly recommended for an extensive review of multiple floating hybrid solutions that have been adopted or are still in the development stage (McTiernan and Sharman, 2020; Saeidtehrani *et al.*, 2022; Taveira-Pinto *et al.*, 2021).

For fixed hybrid structures, scour presents some knowledge gaps (Fazeres-Ferradosa *et al.*, 2021) and, as in OWT complex foundations, scour protection studies are still lacking. The focus has been on the efficiency and hydrodynamic performance of converters rather than on scour behaviour in complex foundations. Nonetheless, scour protections in hybrid structures remain an important topic of research, since:

- Scour represents a threat to the offshore wind structure and the functioning of marine energy converters.
- The eventual accretion of sediments between the converter and the foundation could also lead to an efficiency decrease or malfunctioning of the device, thus reducing its viability.
- Implementation of marine energy converters could lead to softer scour countermeasures, hence reducing costs and expenditures.
- Effective scour protections could optimise the structural behaviour, thus enhancing the usage of hybrid structures.

The literature identifies a significant knowledge gap regarding the design and use of scour protection in hybrid structures.

2.5.1. MARINE ENERGY CONVERTERS

As aforementioned, the synergy between OWT and marine harvesting technologies presents new challenges and research topics. The movement of an oscillatory/rotative body causes additional soil-fluid-structure interactions, since wave-orbital and current velocities change, as downflow pressures and vortices, in the vicinity of the structure. Standard scour patterns and behaviour in offshore foundations are no longer applicable. Therefore, scour protections – static or dynamic – designed with actual knowledge should be misadjusted.

The assessment of the actual design methods for marine energy converters or hybrid structures should include additional variables beyond structural parameters (D_{50} , ρ_s , extent, t_s , S/D) and environmental parameters (d , H_s , T_p , U_c , U_m). They should consider cyclical pressure variations caused by device movement/oscillation, as well as the influence that increases in vibration could have on the structure's natural frequency. The impact of converter motion on soil properties, disturbance of current and tidal velocities, and variations in the flow field are other factors that could significantly influence the design of hybrid structures and scour protection mechanisms.

2.5.1.1. Wave Energy Converters (WECs)

An example of a wave energy converter that induces cyclic variations in motion and pressure is the CECO converter (Rosa-Santos *et al.*, 2019b). By converting its inclined motion into energy, a cycle of upward and downward pressure is initiated (Figure 16), interfering with the flow field, enhancing and decreasing velocities and pressures, and generating horseshoe and lee-wake vortices near the profile bed, mainly behind the foundation (Fazeres-Ferradosa *et al.*, 2021).

Moreover, the movement itself could cause excessive vibratory motion of the pile supporting the WEC. However, the device could reduce scour at the foundation by absorbing wave energy and lowering wave heights. The uncertainty of those facts would call for reinforced scour protection or a softer countermeasure, which should be a motive for further exploratory research to assess whether both structures – a CECO converter and an offshore foundation – could be mutually advantageous.

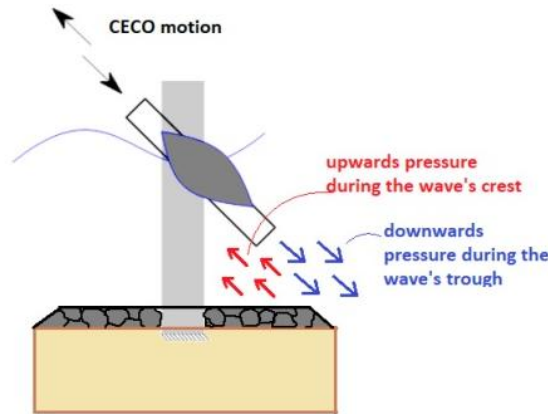


Figure 16 – Scheme of CECO's movement and expected upward/downward pressure action on a scour protection (Fazeres-Ferradosa *et al.*, 2021).

Another WEC that could have a positive impact as a scour-corrective solution is the Oscillating Wave Surge Energy Converter (OWSEC), shown in Figure 17, similar to a floating plate (Zhu *et al.*, 2020). This research assessed the implications and viability of such an energy converter as a protective measure for a pipeline. It concluded that the device could work as a scour-reducing device, depending on characteristics such as size, motion, and other parameters. Thus, the influence of the flap rotation angle (α'), wave height-water depth ratio and water depth-wavelength ratio on seabed changes was also studied (Taheri *et al.*, 2022). By performing a set of tests, it was concluded that:

- By changing α' , from motionless to a rotational body, scour was reduced in length and range, by moving scouring and deposition zones closer to the structure.
- By increasing α' , the flap rotation reduces velocities, leading to less scour and more deposition of sediments. But closer to the device, the flap motion and flow disturbances create vortices, leading to different scour behaviour.
- By increasing the H/d ratio, scour and bed level variations aggravate, concluding that shallow waters or more energetic wave conditions are detrimental to the scour defensive performance of the energy converter.

Therefore, it can be concluded that flap energy converters, compared with similar fixed structures, reduce seabed scour, making them a promising scour countermeasure. However, scour protection may be required to prevent scour-related problems at the WEC's foundation.

It should also be noted that a new floating two-flap OWSEC system (Figure 18) has been tested by Bosma *et al.* (2016), Ruehl *et al.* (2019), and Coe *et al.* (2020), the so-called Floating Oscillating Surge Wave Energy Converter (FOSWEC). At the initial testing stage, the device was attached to a constraint platform that could lock/unlock different allowable degrees of freedom (DOF), Bosma *et al.* (2016) and

Ruehl *et al.* (2019). In the second stage, the device was tested using mooring lines (Coe *et al.*, 2020). Loads, the motion of the flaps, platform, and mooring behaviour, power-take-off (PTO) components, and incident wave fields were characterised using irregular/regular wave response tests. The implementation of a similar bottom-fixed version could be an interesting upgrade as a scour countermeasure to single-flap OWSEC.

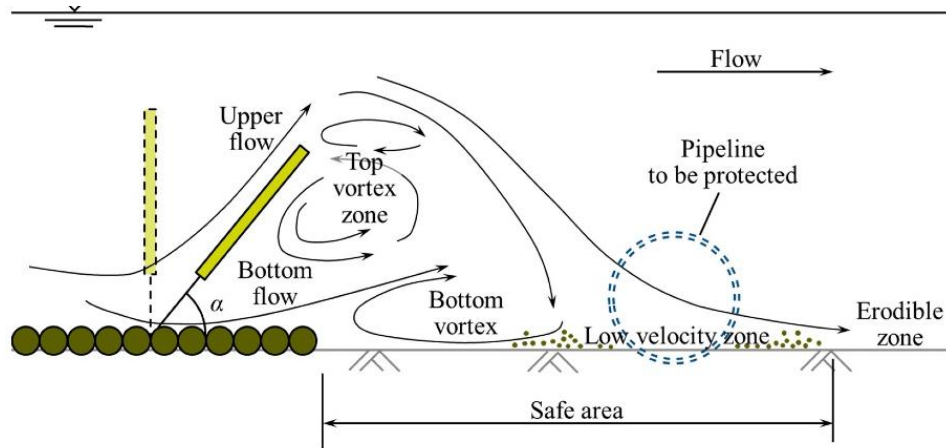


Figure 17 – Scheme of working mechanism of a bottom-mounted OWSEC (Zhu *et al.*, 2020).

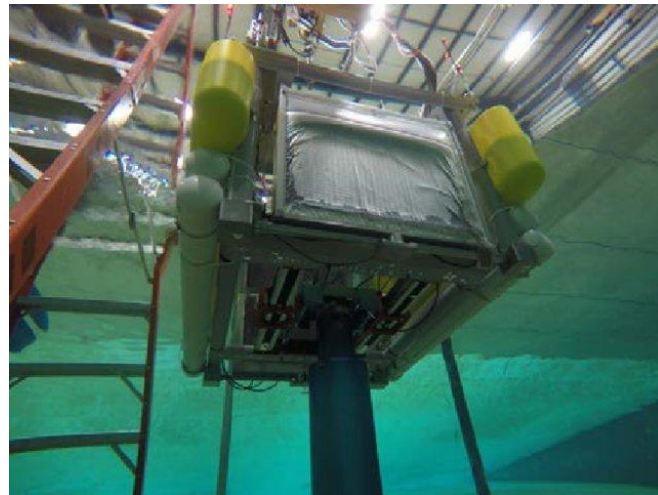


Figure 18 – Underwater view of the FOSWEC device (Bosma *et al.*, 2016).

Oscillating water columns (OWC) have been studied quite extensively in the last few years. Mainly integrated into breakwaters or sea walls, some literature reviewed scour patterns for gravity-based OWC-WEC (Lancaster *et al.*, 2020; Lancaster *et al.*, 2022). A detailed review of the findings can be seen in Fazeres-Ferradosa *et al.* (2021). However, the model was updated by adding two lateral pontoons, flop valves, and a chamber flap door (Lancaster *et al.*, 2022). By testing different configurations of the pontoons and the presence/absence of chamber doors, for different sets of conditions, it was concluded that:

- Even with the presence of the pontoons, scour compromised the back corners of the structure, for all the conditions tested, since downstream scour is regulated by flow contractions and vortex developments.
- Curve-edged pontoons represented 23% of scour reduction when compared to sharp-edged pontoons.
- The scour hole formation led to settlements of the structure.

These findings indicate that hydrodynamic structural improvements to energy converters and offshore foundations could reduce scour in their vicinity, thereby reducing the need for new, softer scour protection measures. Moreover, both studies advise some form of seabed preparation or scour protection to prevent settlements. These observations align with the conclusions of Van Velzen *et al.* (2016), Van Velzen and Bruinsma (2017), and Bruinsma *et al.* (2018).

Another type of wave energy technology extensively studied in the literature is the Wavestar (Kramer *et al.*, 2011), a point-absorber WEC that generates electricity through the oscillatory motion of a hemispherical buoy driven by a PTO system (Figure 19). The structure can only move in a single DOF, along the pitch axis, thereby reducing its complexity, application, and behaviour analysis. A multitude of physical/numerical experiments and real-sea tests were conducted over the years (Ambuehl *et al.*, 2013; Jakobsen *et al.*, 2016; Kramer *et al.*, 2011; Ransley *et al.*, 2017; Vidal Sanchez *et al.*, 2012; Zurkinden *et al.*, 2013).

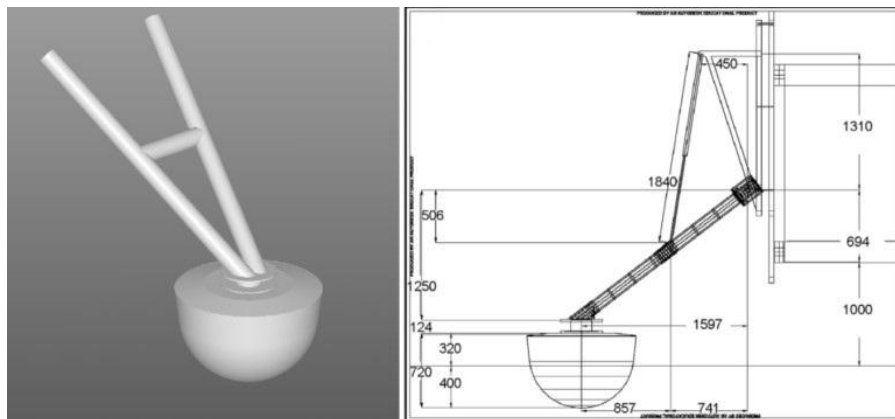


Figure 19 – Wavestar Model (adapted from Ransley *et al.*, 2017).

By analysing the surface elevation in the wake region of the model, the physical and numerical models of Ransley *et al.* (2017) show that this type of device reduces the wave height behind the buoy by a considerable amount, suggesting significant diffraction effects, particularly for high-frequency waves. However, a significant difference was observed between the physical and numerical models regarding scattered or radiating waves. The physical model registered minimal scattering, while the numerical model showed some evidence: flattening crests/troughs close to the device and sharpening of flattening crests/troughs further from the device, for long waves; an increase of the wave height close to the device and a slight drift out of phase further from the float.

These differences between the models were attributed to the lack of absorption at the boundaries of the numerical domain, which may have led to excessive reflections. As previously mentioned, in the CECO

case, the Wavestar device's absorbing and wave-reducing capacity has the potential to serve as a scour countermeasure or, at a minimum, work in symbiosis with other scour protection or countermeasures, creating an interesting research opportunity.

2.5.1.2. Tidal/current energy converters (TECs)

As WECs show to be a viable option to reduce scour when combined with OWT, TECs, on the other hand, represent a meaningful challenge since they induce some effects – the rotor may block the flow causing acceleration in current velocities, the wake effect of the turbine may alter hydrodynamics, and the enhanced turbulence could increase shear stress at the seabed vicinity –, thus enhancing scour around the structure (Chen and Lam, 2014; Kang *et al.*, 2012; Neill *et al.*, 2009). However, scour protection studies in TECs are non-existent to the authors' knowledge; however, there is some information on scour in TECs, based mainly on experience with ships' propellers or turbines fixed to single piles.

The rotor's effect, the increased wake effect under the turbine, and the tip clearance – the distance between the tip of a rotating blade to a stationary part, point, or object – are pointed out as the main considerations for scour induced by TECs (Chen and Lam, 2014). These findings are supported by Chen *et al.* (2017), who examined the influence of tip clearance on scour around a pile-supported horizontal-axis turbine. The rotational movement of turbines has been shown to increase downflow velocities and the occurrence of horseshoe vortices, thereby amplifying shear stresses (Chen *et al.*, 2017; Hill *et al.*, 2014; Sun *et al.*, 2018). By comparing three different tip clearance distances, results showed that shorter distances to the bed profile led to a faster scour extent of up to $1D_t$ downstream and $0.5D_t$ on both sides (Chen *et al.*, 2017), where D_t is the turbine disc diameter.

Similar research on a Darrieus-type vertical-axis turbine to assess scour parameters was conducted for different tip clearance distances and distinct turbine radii (Sun *et al.*, 2018). The results were in line with Chen *et al.* (2017), as the decrease in tip clearance also led to higher scour rates – a 10%-20% increase in scour extent and a 30% increase in scour depth. Moreover, it was concluded that equilibrium scour is independent of tip clearance, since a continuous decrease of the distance to the sediment bed, at a certain point, does not translate to a significant increase in scour depth – the live bed scour effect takes control.

Considering the influence of the rotor radius, it was concluded that with the radius increment, maximum scour depths decrease at first and then increase (Sun *et al.*, 2018) – Table 7; as for the tip clearance, scour increases in depth and extent with the decrease of the parameter (Table 8).

The maximum scour depth was observed for a small rotor radius, and $C/H_r = 0.5$ (Sun *et al.*, 2018), where C is the tip clearance distance, and H_r is the height of the turbine rotor. As for the minimum scour ($1.6D$), it was obtained at the maximum rotor radius when the distance to the bed was equal to the rotor height. This indicates that, to minimise the prejudicial effect that TECs have on scour, these devices should be placed on OWTs at a relatively high distance from the seabed.

The performance analysis of TECs by Chen *et al.* (2017) and Sun *et al.* (2018) was conducted only under current conditions. The results presented in Table 7 showed that tidal current devices can be detrimental to offshore foundations, reinforcing the need for scour protection (Chen *et al.*, 2013). The empirical formulas for predicting scour in tidal current turbines (Chen *et al.*, 2017; Sun *et al.*, 2018) provide a good starting point for developing new proposals for scour protection for TECs.

Table 7 – Influence of rotor radius on scour for $C/H_r=0.5$ (Sun *et al.*, 2018).

Rotor radius	37.4 mm	45.9 mm	56.3 mm
S/D	2.6	2	2.2
Scour relative to a pile ($S/D = 1.45$)	+ 78.9%	+ 37.5%	+ 51.3%

Table 8 – Influence of tip clearance on scour for $H_r=56.3$ mm (Sun *et al.*, 2018).

C/H_r	1.00	0.75	0.50	0.25
S/D	1.6	1.7	2.2	2.2
Scour relative to a pile ($S/D = 1.45$)	+ 9.9%	+ 16.8%	+ 51.3%	+ 51.3%
Scour extent (downstream)	4.6D	4.8D	8.5D	10.0D

A scour reduction for a monopile offshore foundation was proposed by installing a tidal current converter at an optimal position in front of the monopile, facing the current (Charlier, 2003). In addition to reducing shear stress, the device also reduces the maximum scour depth. It was reported that scour evolves more slowly and is amplified farther from the rotor when the device is placed downstream of the foundation (Hill *et al.*, 2014).

These opposing opinions underscore the need for further research to clarify some contradictions and ensure that scour protections are accounted for in the optimisation of tidal current energy converters.

2.5.2. HYBRID STRUCTURES

In the literature, WECs are included in maritime structures such as breakwaters, sea walls, and harbours. It was concluded that for the toe region, erosion and sediment transport due to wave reflection, breaking, and splashing are increased (Mustapa *et al.*, 2017). Therefore, countermeasures against scour in these sectors are necessary.

The research by Rosa-Santos *et al.* (2019a) on a rubble-mound hybrid system proposed for the extension of the North Breakwater of the Port of Leixões (PT), which integrates an OWC energy converter, was a very promising case of a maritime hybrid structure. The physical model, with a geometric scale of 1:50, was used to assess overtopping, structural stability and functionality under extreme onshore conditions, wave reflection performance, and hydrokinetic efficiency for three different converter geometries. However, by reproducing the seabed bathymetry in front of the breakwater, it was possible to monitor and analyse scour at the breakwater's toe. Although differences in the bathymetric profiles were detected after 6000 waves, the authors concluded that there was no definitive evidence of scour at the toe, with or without the WEC module installed. The sand ripples and the displacement of some of the Antifer block were identified as the main reasons for the variations observed in the bathymetric profiles. Nonetheless, this study emphasises the value of monitoring scour at the cross-section of these types of coastal hybrid structures.

A soft-scour countermeasure was implemented by adding a coastal cage net for aquaculture on an offshore jacket (Hsin-Hung *et al.*, 2014). The concept of offshore aquaculture has developed over the

last few years and has gained significant momentum. The conclusions drawn help prevent scour around the foundation. For a 100-year return period wave-current condition, the maximum scour depth was reduced from $1.17D$ (without the cage) to $0.75D$ and $0.71D$ – one cage at the current side and one net at the current side and another at the wave side, respectively – representing 35% to 39% of scour depth reduction (Hsin-Hung *et al.*, 2014).

A combination of an OWSEC with an OWT foundation (monopile and GBF), as shown in Figure 20, was used to assess scour under wave and current action in layered soils (Miranda, 2022). The study was performed on a physical model at a 1:50 geometrical scale, with a WEC device integrated at the upstream side of both foundations.

The converter was placed at further distances from both foundations during the set of 16 tests. The results obtained (Table 9) were compared with those from a setup without the device. Overall, an average reduction of the scour depth – 60% and 33% for the monopile and GBF, respectively – was obtained with the presence of the wave flap energy converter in front of both foundations for a fine sand seabed (Miranda, 2022). For a layered soil, a 65% decrease (monopile) and a 67% decrease (GBF) in scour depth were observed. Even though scour protection was not incorporated, the values suggest that this approach could and should be considered as a scour countermeasure. It seems viable and could lead to the implementation of a less extensive, thicker rip-rap protection, reinforcing the idea that static protections may not be necessary and resulting in considerable cost reductions.

Furthermore, Miranda (2022) states that:

- For the monopile, scour depth presented a higher value for fine sand instead of for the layered soil, without the device. With the presence of the WEC, the difference in scour depth between fine sand and layered soil was eliminated.
- For the GBF, without the OWSEC, the scour depth was similar for both soils. As a result of implementing the device, the layered soil experienced lower values of scour.
- A direct correlation between the WEC distance and scour depth was not possible to establish. Nonetheless, the device's incorporation increased sediment deposition between the converter and the foundations.

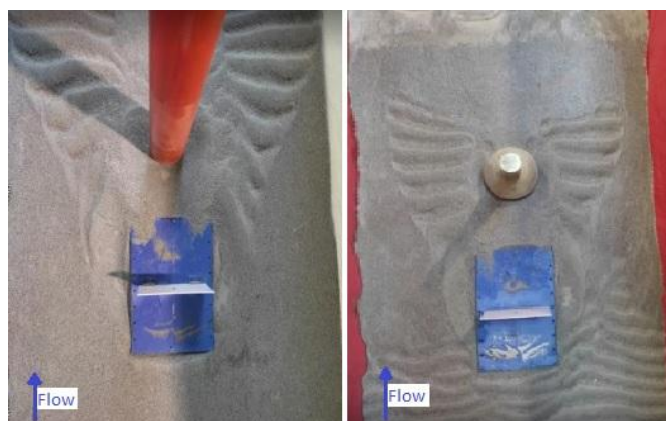


Figure 20 – Hybrid monopile and hybrid GBF foundations (adapted from Miranda, 2022).

Table 9 – Physical modelling study of a hybrid monopile and hybrid GBF system – prototype values (Miranda, 2022).

Type of soil	Fine sand bed	Layered soil
Scale	1:50	
d (m)	18	
T_p (s)	[9.31 – 10.27]	[9.31 – 10.35]
U_c (m/s)	1.22	
Type of Waves	Irregular	
H_{m0} (m)	[4.65 – 5.1]	[4.4 – 4.85]
U_m (m/s)	[0.785 – 0.919]	[0.757 – 0.898]
U_{cw}	[0.570 – 0.608]	[0.575 – 0.616]
Duration	3000 waves	
Wave-current direction	0°	
D (m)	Monopile: 5.5 GBF: 9	
Converter	OWSEC: 7.5 m x 5 m flap	
Model distance to the foundation	[7.5, 12.5, 17.5] m	
S (Monopile)	No WEC: 1.65 m WEC: [0.65 – 0.75] m	No WEC: 2.5 m WEC: [0.65 – 0.9] m
S/D (Monopile)	No WEC: 0.30 WEC: [0.12 – 0.14]	No WEC: 0.45 WEC: [0.12 – 0.16]
S (GBF)	No WEC: 0.8 m WEC: [0.5 – 0.55] m	No WEC: 0.9 m WEC: [0.15 – 0.45] m
S/D (GBF)	No WEC: 0.09 WEC: 0.06	No WEC: 0.10 WEC: [0.02 – 0.04]
Scour protection	Not applied	

Another hybrid structure study was performed by Jiang *et al.* (2023). It consisted of a 5-DOF numerical study and a physical numerical study of a 4-legged jacket coupled with three oscillating buoys (Figure 21), similar to those of Kramer *et al.* (2011) and Ransley *et al.* (2017), using a swing arm with a hinge connection. A numerical model and a 1:8 geometric-scaled physical model were performed, focusing on the structural response, the motion of the WEC, the energy transfer and distribution to the structure due to the WEC's motion, and the stability analysis of the hybrid structure. The conclusions extracted by Jiang *et al.* (2023) are as follows:

- When the incident wave period is close to the resonance frequency of the buoy, phenomena such as wave overtopping and impact of the WEC re-entering the water surface were registered.
- Extreme waves did not cause significant damage to the structure.
- For a constant wave period, as the wave height increases, the energy distribution percentage of the piles increases, opposite to the energy distribution of the tower (decreases).
- The piles heading the waves suffer more from the action of waves and the buoy motion.
- The buoy motion has an impact on the piles, but a small effect on the wind turbine tower.

- The piles heading the waves sustain most of the energy under environmental loads and excitation of the WEC, when compared to the back piles, but mainly when compared to the tower.

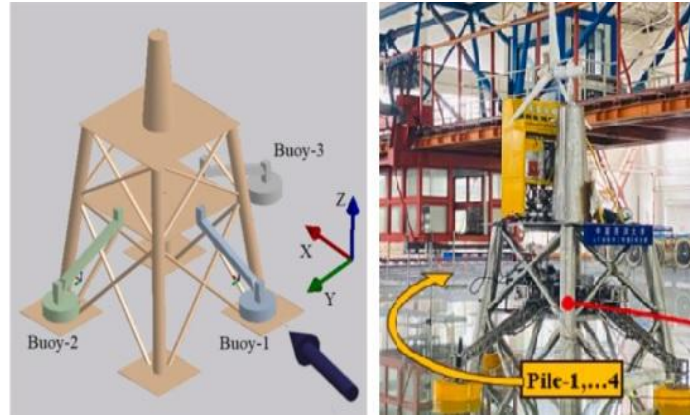


Figure 21 – Hybrid 4-legged jacket foundation coupled with WECs (adapted from Jiang *et al.*, 2023).

Khatibani and Ketabdari (2022) recently proposed an innovative hybrid structure (Figure 22) that combines a monopile with two pitching-type WECs inspired by two commercial OWSEC concepts (Oysters™ and DEXAWAVE™). The connections between the devices and the monopile allow the floating device to move along the heave and pitch axis (restricting their surge, sway, roll, and yaw motions). The author developed a numerical model, which was validated using data reported to the Wavestar model by Jakobsen *et al.* (2016). It was concluded that the converters effectively absorbed part of the incident wave energy (maximum value – 407 kW, median value – 364 kW), that the hybrid structure produces 26.44% more renewable power than a monopile wind turbine foundation, and that no resonance effects were observed.

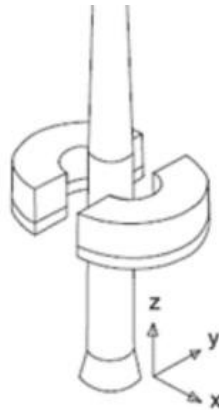


Figure 22 – Conceptual design of a monopile hybrid structure (adapted from Khatibani and Ketabdari, 2022).

Although the studies by Jiang *et al.* (2023) and Khatibani and Ketabdari (2022) were not focused on scour or did not analyse the potential of WECs as scour countermeasures, they helped us understand the joint behaviour of a hybrid structure under offshore conditions. It is possible to recognise that energy

converters influence the overall behaviour of a hybrid structure without compromising its safety. In fact, they absorb and decrease part of the wave impact and energy applied directly to the structure and transfer it to the foundation. However, an extensive study should be conducted to determine whether this energy transfer to the piles could enhance scour by increasing vibrations.

2.6. CFD MODELS FOR SCOUR AND SCOUR PROTECTIONS ANALYSIS

As a powerful computational tool, Computational Fluid Dynamics (CFD) enables us to analyse and solve complex flow problems. CFD software employs mathematical equations, numerical methods, algorithms, and computer simulations to analyse and predict the behaviour of fluid flows in a physical case. However, these models can be extremely time-consuming if not applied properly. An incorrect implementation without validating physical models could yield misleading results. The two form a pair of complementary tools.

As governing equations, the Navier-Stokes equations (NSE) are used on CFD models to guarantee the conservation of:

- Mass (Continuity law) – Equation 14.
- Momentum (Newton's 2nd law) – Equation 15.
- Energy (1st law of thermodynamics) – Equation 16.

The equations can be derived as follows:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho u) = 0 \quad (14)$$

$$\frac{\partial \rho u}{\partial t} + \nabla \cdot (\rho u u) = -\nabla p + \nabla \cdot \tau + F \quad (15)$$

$$\frac{\partial}{\partial t} \left[\rho \left(e + \frac{1}{2} u^2 \right) \right] + \nabla \cdot \left[\rho u \left(e + \frac{1}{2} u^2 \right) \right] = -\nabla \cdot (k \nabla T) + \nabla \cdot (-p u + \tau \cdot u) + u \cdot F + Q \quad (16)$$

where u represents the velocity of the flow, p the fluid pressure, ρ the fluid density, τ the stressor tensor, F the external forces applied to the fluid, T the temperature, κ the turbulent kinetic energy, e the internal energy, and Q the energy supplied to the system as heat. For incompressible fluids, Equations 14 and 15 can be simplified into Equations 17 and 18, where μ represents the dynamic viscosity:

$$\nabla \cdot u = 0 \quad (17)$$

$$\rho \frac{\partial u}{\partial t} + \rho u \cdot \nabla(u) = -\nabla p + \nabla \cdot (\mu(\nabla u + \nabla u^T)) + F \quad (18)$$

The two significant types of flow regimes can be distinguished considering the Reynolds number (Re):

- **Laminar ($Re < 2000$):** fluid represents regular trajectories, fluid particles do not cross each other, velocity variations are extremely slow in time (or almost non-existent), and flow is dominated by viscosity effects (Webber, 1971).

- **Turbulent ($Re > 4000$):** fluid particles have abrupt variations in space and time, the velocity field is also variable in space and time, and the regime is separated from the boundary surface by a laminar boundary sub-layer in which the flow presents laminar behaviour (Brkić and Praks, 2018).

The majority, if not all, of coastal engineering problems deal with turbulent regimes. However, turbulence modelling is one of the most challenging aspects of CFD, yet crucial, since correct and reliable results depend on its proper modelling. The most well-known turbulence models can be summarised as follows:

- **Reynolds-Averaged Navier-Stokes (RANS):** based on average values of variables for both steady-state and dynamic flows.
- **Direct Numerical Simulations (DNS):** application of fluctuated values into the Navier-Stokes equations without a turbulence model.
- **Large Eddy Simulations (LES):** intermediate model between the RANS and DNS. It uses filtered Navier-Stokes equations for large-scale eddies.

As the most widely used turbulence model, RANS models are commonly applied in coastal engineering, primarily to characterise the flow field around structures. More specifically, the following models can be highlighted to simulate turbulent flows:

- **k - ϵ models:** consider both the turbulent kinetic energy and dissipation, use wall functions, show good convergence, have low memory requirements, are convenient for (in)compressible flows, and present flow interactions with complex geometries.
- **k - ω models:** consider both the turbulent kinetic energy and dissipation, use wall functions, are convenient for internal and separate flows, are hard to converge, and behave with high sensitivity to the initial conditions.
- **k - ω SST (shear stress transport) models:** account for the transport of the principal shear stress in adverse pressure gradient boundary layers.
- **LES Smagorinsky models:** self-similarity theory, solves small eddies with a sub-grid scale model based on geometry calculation.

The first numerical model studies on scour were reviewed by Sumer (2007, 2015). Nowadays, CFD scour models with waves and/or currents are based on more advanced models (*e.g.*, RANS-VOF) that correctly represent the motion of the free surface. A detailed review of wave-structure-seabed interactions was made by Diaz-Carrasco *et al.* (2021).

Regarding scour and sediment transport, the existing numerical models can be divided as follows (Zhao, 2022):

- **Sediment transport rate models:** one-phase model, as the flow and the scour model are independent. Sediment motion on the water is assumed not to affect the flow. The sediment transport rate is calculated as the volume of sediment that passes per unit width of the flow. They are the most used, most accurate, and most efficient type of models.
- **Equilibrium scour models:** the first generation of models. It allows for easy prediction of the scour profile at the equilibrium stage, but cannot capture the full scour development behaviour. In real-life situations, structures fail before scour reaches equilibrium, or the duration of a storm is not sufficient to reach it. Therefore, it is an incomplete model.

- **Two-phase flow models:** allow for the simulation of the flow and sediment phases and are suitable for sheet-flow conditions caused by high flow velocities. In this type of model, continuity and momentum equations for the flow and sediment phase are the governing equations. However, their lack of use is credited to the slow computational speed.
- **CFD-DEM models:** a novel approach that combines the Discrete Element Method (DEM) and CFD for simulating local scour around the structure. DEM allows us to predict the motion of each sediment particle. The water flow is simulated using CFD, and the motion of sediment particles is modelled using equations of motion that account for fluid drag, gravity, and particle-particle collision forces. However, these models require significant computational time/cost.
- **Depth-averaged models:** developed to simplify large-scale problems to reduce computational cost/time. They solve shallow water equations to simulate flow. Since these flow equations are depth-averaged, they fail to capture flow variations across the water depth and cannot directly predict complex flow features, such as horseshoe vortices. Therefore, it requires modifications to simulate scour around a structure.

Scour and sediment transport still represent a considerable challenge in numerical modelling, although they have been widely used across the scientific and professional communities with solid results (Sumer, 2015). Most numerical model studies (Table 10 and Table 11), regarding OWT or OF, focus on the structural behaviour and the structural repercussions of scour (Menéndez-Vicente *et al.*, 2023; Prendergast *et al.*, 2015), or the impact of scour protections on the structural response of the foundation (Khansari *et al.*, 2022; Ma and Chen, 2021; Mayall *et al.*, 2018). However, the lack of research on scour protection behaviour and damage to OF constitutes a significant knowledge gap in the literature, as it introduces additional variables, thereby increasing the problem's complexity. In fact, there are almost no studies on (riprap) scour protection, as modelling its failure involves added complexity.

Developing models capable of addressing such small domains is not only expensive but also time-consuming. Furthermore, the necessity to model the filter layer and its interaction with the armour-layer material, as well as to consider seabed mobility. Not to mention even more intricate scenarios, such as layered soils, wide-graded protections, and the use of complex geometries (Fazeres-Ferradosa *et al.*, 2021). Nevertheless, numerical models could offer a highly valuable alternative for evaluating scour-related parameters in scour protection, such as pore pressure, shear stress, and flow velocity. Frequently, these variables pose some challenges regarding an accurate measurement within the physical models, as they need to use submerged load cells and other intrusive equipment and sensors, potentially disrupting the natural behaviour of the sediment dynamics, thus skewing scour depths within and around the protection's surroundings (Fazeres-Ferradosa *et al.*, 2021).

In summary, this review shows that, in the literature, numerical models place strong emphasis on scour, particularly under wave conditions alone. Furthermore, when considering multiple hydrodynamic conditions, they are usually investigated separately. It is also worth noting that most studies make use of open-source CFD software, such as OpenFOAM and REEF3D. However, the modelling of riprap scour protection is scarce and has shown limited effectiveness – simplified models that do not assess the damage to the armour layer and consider only currents, rather than waves or waves and currents. Nevertheless, it is important to note that these studies support the viability of modelling such a type of protection. As for the turbulence models, most studies used a RANS model, with the $k-\omega$ model particularly useful for simulating turbulent flow behaviour, as previously stated.

Table 10 - Numerical models performed on scour and scour protection for OS – Part 1.

Reference	CFD Software	NSE (Turbulence Model)	Topic	Application
Nielsen <i>et al.</i> (2013)	Flow3D	RANS (RNG $k-\epsilon$)	Scour Protection (Riprap) Monopile Currents	A novel approach that proved that flow and bed shear stresses in a scour protection around a monopile can be modelled. Spheres and porous media model scour protection. Porous media was found to capture the overall results at a lower computational cost, but it requires calibration. Damage to protection is not covered.
Arboleda-Chavez <i>et al.</i> (2018)	Open FOAM	VARANS (Not provided)	Scour Protection (Riprap) Monopile Currents	A porous media flow model that shows a good agreement until a certain depth. The model requires further development and updates. Damage to the protection is not covered.
Yu <i>et al.</i> (2020)	Flow3D	RANS (RNG $k-\epsilon$)	Scour Protection (USAF) Monopile Waves Currents	Study of a new type of scour countermeasure, validated with physical model experimental measurements. Compared to a typical monopile foundation, the USAF and its anchoring effectively block the occurrence of scour in front of the structure, and the maximum scour only occurs downstream of the pile.
Ahmad <i>et al.</i> (2015)	REEF3D	RANS ($k-\omega$)	Scour Monopile Waves	Analysis of local scour under waves for different KC values. Free surface profile and bed topography captured using the level set method. Good agreement with experimental data. Allows for the prediction of maximum scour depth and location with reasonable accuracy. Scour increases with KC . Found that horseshoe vortex and wake shedding do not contribute to local scour for low KC numbers.
Afzal <i>et al.</i> (2015)			Scour Pier pile Waves Currents	Use of the sediment transport module to calculate scour patterns, time development, and depth for pier piles for currents or waves. Validated with experimental results. Slight difference in scour pattern for the pier under constant discharge, justified by the lack of measurements of the bed topography outside the scour hole in the physical model.
Ahmad <i>et al.</i> (2018)			Scour Monopiles Waves	Simulation of wave-induced scour for one pile and between piles in a side-by-side arrangement for different distances. Demonstrates that small and full-sized numerical water tanks (NWT) both allow a full development of waves and scour. Validated with experimental data. The formation of the jet effect is discussed.
Gautam <i>et al.</i> (2021)			Scour Monopile Waves Currents	Scour analysis for different combinations of hydrodynamic conditions. Validated with experimental data. Results show that scour due to waves with weak or mild currents does not significantly differ from scour due to waves with strong currents. However, for current-dominated wave-current conditions, scour varies substantially. For high KC values, scour also increases with U_{cw} .
Ahmad <i>et al.</i> (2019a)			Scour Jacket Waves Currents	A numerical model that assesses the S/D values for a 4-legged jacket (for waves-only and current-only). The model was validated using previous models. Results showed good agreement with field measurements. Allowed us to understand the main scour patterns around the foundation, highlighting the areas of significant risk.

Table 11 - Numerical models performed on scour and scour protection for OS – Part 2.

Reference	CFD Software	NSE (Turbulence Model)	Topic	Application
Gautam <i>et al.</i> (2021)	REEF3D	RANS (k- ω)	Scour Monopile Waves Currents	Scour analysis for different combinations of hydrodynamic conditions. Validated with experimental data. Results show that scour due to waves with weak or mild currents does not significantly differ from scour due to waves with strong currents. However, for current-dominated wave-current conditions, scour varies substantially. For high KC values, scour also increases with U_{cw} .
Ahmad <i>et al.</i> (2019a)			Scour Jacket Waves Currents	A numerical model that assesses the S/D values for a 4-legged jacket (for waves-only and current-only). The model was validated using previous models. Results showed good agreement with field measurements. Allowed us to understand the main scour patterns around the foundation, highlighting the areas of significant risk.
Lian <i>et al.</i> (2022)	Flow3D	RANS (RNG k- ϵ)	Scour Jacket Currents	3D model of a multi-bucket jacket foundation. Simulation results for a single pile show good agreement with experimental results, for validation purposes. Results showed that structural features of the buckets, such as exposed height, diameter, and upper-structure deviation, could influence the scour depth.
Stahlman <i>n</i> (2014)	Open FOAM	RANS (k- ω SST)	Scour Tripod Waves Currents	A multi-phase fluid flow model that included bed load and suspended load transport processes for a tripod foundation. Simulated scour development for wave loads and current loads. Validated against numerical and experimental data on scour around a monopile. Results showed the main scour patterns and depths around the foundation, highlighting the areas of major risk.
Hu <i>et al.</i> (2022)	Not provided	RANS (RNG k- ϵ)	Scour Tripod Waves	Analyses the scour characteristics and flow velocity distributions for a tripod foundation in random waves. The model accurately portrays the scour process and the flow field. The model showed that the blockage effect of tripod structural features increases turbulence and shear stress under the main column and lower diagonal braces, resulting in more severe scour patterns and depths. Shows good agreement with other numerical and experimental data. It could need revision for larger KC conditions.
Wilms <i>et al.</i> (2012)	Open FOAM	RANS-VOF (k- ω)	Scour Protection STRABAG Waves Currents	Analysis of velocities, shear stresses, and stability of scour protection system for waves and wave-currents hydrodynamic conditions. Good agreement with the findings of the physical model experiment. No scour depth or pattern is analysed
Dutta <i>et al.</i> (2023)	REEF3D	URANS (k- ω)	Scour Rectangular piles Waves Currents	Scour investigation around rectangular piles with different ratios. Employs a level-set approach to realistically capture the free surface. Applies a morphological module that employs a modified critical shear stress formula for erosion and deposition calculations. Model accuracy is confirmed by comparing model results with experimental results from a pile. Demonstrates that scour depth increases with the increase in the KC number for a fixed U_{cw} .
Ahmad <i>et al.</i> (2019b)		RANS (k- ω)	Scour Pipelines Waves Currents	Prediction of scour under currents, waves, and a combination of both. The model was validated against experimental observations, and its results showed good agreement with physical model values. Found that scour depth and extent below a pipeline increase with U_{cw} for fixed KC .

2.7. PROBABILISTIC DESIGN OF SCOUR PROTECTIONS

2.7.1. HORNS REV 3 AND EGMOND AAN ZEE: A CASE COMPARISON

Existing semi-empirical design methods have, to some extent, uncertainty regarding scour phenomena due to the lack of long-term *in situ* data. This often results in conservative, costly solutions and an inaccurate perception of the protection's reliability over its design life. To reduce excessive installation costs and evaluate the potential optimisation of the armour layer material in rip-rap protections, Fazeres-Ferradosa *et al.* (2018b) introduced a probabilistic methodology that enables the calculation of the failure probability (P_f) of an existing scour protection or the determination of the D_{50} for a target P_f value. The methodology was developed using data from the Horns Rev 3 offshore wind farm, and the results showed that, for the same safety level, a static scour protection could be optimised to have a dynamically stable armour layer. This optimisation resulted in a reduction of the median stone size by approximately 52%, from 0.54 m to 0.26 m. Fazeres-Ferradosa *et al.* (2018b) concluded that any D_{50} value within this range could achieve low P_f values (on the order of 10^{-4}).

The probabilistic methodology was extended to a new case study, the Egmond aan Zee offshore wind farm. The methodology employed a Monte-Carlo simulation based on hindcast metocean data to model the environment, generating pairs of H_s and T_p to assess the protection's response in terms of S_{3D} using Equation (4). A description of the methodology used is provided in Appendix I.



Figure 23 – Egmond aan Zee (left) and Horns Rev 3 (right) locations (Chambel *et al.*, 2022).

The results indicated that, for the same D_{50} , the failure probability can differ significantly between the two case studies. For instance, for $D_{50} = 0.30$ m, it was found that P_f varies by up to two orders of magnitude, from 2.95×10^{-4} for Horns Rev 3 to 4.8×10^{-6} for Egmond aan Zee. In the latter case, median stone sizes greater than 0.38 m were associated with a virtually zero probability of failure.

According to Fazeres-Ferradosa *et al.* (2018b) and Esteban *et al.* (2019), the scour protection at both locations was designed using a static design criterion, which allowed no movement of the stones. This design used D_{50} values of 0.35 m (HornsRev3) and 0.40 m (Egmond aan Zee). Variations in D_{50} design may stem from hydrodynamic and local conditions, as well as from differing return periods assumed for the local currents, which are usually set to 50 years for wave heights and periods. No information was found on the actual return periods used in either case. Nonetheless, the results indicated a probability of filter-layer exposure of approximately 10^{-4} for Horns Rev 3. For Egmond aan Zee, the chance of failure was effectively negligible.

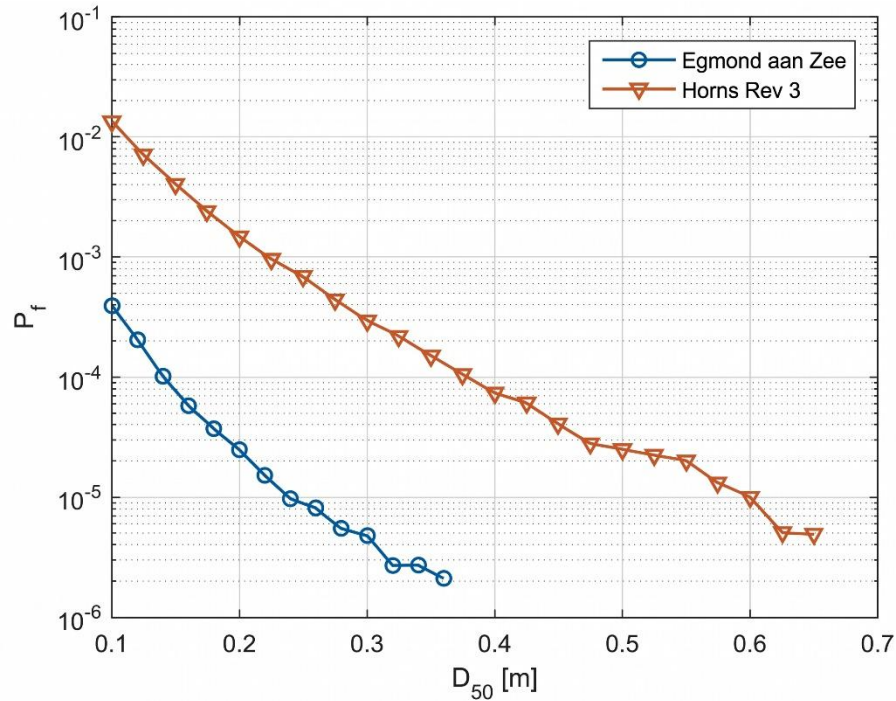


Figure 24 – Comparison of P_f values for both locations, considering the De Vos *et al.* (2012) dynamic criterion – adapted from Chambel *et al.* (2022).

It was determined that the likelihood of a widespread failure of the scour protection was quite low, especially considering that the failure probability for dynamic stability is also minimal (around 10^{-4} or less). For such a low probability, even if movement occurs within the armour layer—that is, static stability is not maintained—the likelihood of exposing the filter layer above $4D_{n50}^2$ remains low. Furthermore, the results indicated that Egmond aan Zee could indeed support a substantial reduction in its D_{50} , potentially decreasing from 0.40 to 0.24 m (a 40% reduction), which would result in a probability of failure around 10^{-6} , quite low compared to other cases documented in the literature, such as Fazeres-Ferradosa *et al.* (2018b, 2019c). For Horns Rev 3, it was observed that the D_{50} could be optimised to some extent based on the acceptable failure probability set by the designer. For example, reducing the D_{50} from 0.35 to 0.30 m could be considered (a 14% reduction).

Regarding the acceptable probability of failure, Fazeres-Ferradosa *et al.* (2018b, 2019c) discussed that P_f around 10^{-4} could serve as a reference value for probabilistic design and reliability assessment. The results indicate that the Egmond aan Zee case has even lower failure probability values. Field studies by Raaijmakers *et al.* (2009, 2010) and Peterson (2014) reported scour occurrence in some offshore monopile foundations up to 2,500 days after installation. However, the maximum scour depth of about $0.6D$ was caused by edge scour, thereby reducing the extent of protection. The formulation for dynamic stability developed by De Vos *et al.* (2012) does not account for this failure mode. The fact that the median stone size at Egmond aan Zee could be reduced, relative to the erosion of the armour layer, could contribute to a decrease in the reported edge scour severity, since smaller armour stone sizes can be related to smaller changes in the seabed roughness. Additionally, reducing the median stone size might lead to a decrease in the protection's thickness, which may also contribute to reduced edge scour.

2.8. CONCLUSIONS

This literature review allowed us to present the latest findings on scour phenomena and protection measures related to offshore and marine harvesting technologies, and to summarise the most recent knowledge gaps and research, particularly in offshore wind turbine foundations, with a special focus on complex and hybrid structures. Several challenges and potential future developments were identified through a brief analysis of the most recent developments in scour protection for OWT. It was intended to show that the topics listed here can support and serve as a basis for upcoming research, development, and optimisation of scour protection for complex and hybrid OWT structures in a marine environment, possibly leading to lower costs and higher performance of offshore and marine harvesting technologies.

Overall, the following conclusions can be presented:

- The study of scour around monopiles has been extensively covered in the literature, although complex hydrodynamic conditions are rarely contemplated. The prediction of scour effects frequently relies on simplified hydraulic conditions, waves and/or currents. There is limited understanding of the effects of real hydraulic conditions, such as simulated tidal flow and multidirectional waves, on the scouring process.
- Although in recent years the discussion regarding scour on complex foundations has grown, some of the approaches used in actual situations are monopile-related. There is a need for further understanding, as higher global and local scour depths were observed in complex structures compared with the average monopile scour depth (Welzel, 2021).
- A lack of a general understanding of the scour development process at complex structures, such as the time scale, the equilibrium scour depth, and other topics related to global/local scour, was identified. Many studies on scour in complex OWT structures focus only on the evolution of maximum scour depths. There is a lack of data on spatial changes in the seabed around complex structures, or such data merely show variations in bed topography. The analysis of spatial variations in scour depth, erosion/deposition patterns, local/global scour depths, the interaction between local and global scour, and the influence of structural design features on spatial changes in scour depth is often overlooked.
- The estimation of spatial and temporal scour depth variations is also performed as a prerequisite for determining whether scour protections are required. The scour protection stability assessment is a crucial part of the design procedure. Nonetheless, only a few studies have focused on major improvements in stability evaluation, damage characterisation, and the scale effects associated with applying small-scale physical model test results to *in situ*/prototype conditions.
- Traditionally, static scour protections are the most used and studied type of protection, despite being based on some sort of empirical concepts, such as the amplification factor, to consider the foundation's effects in enhancing the scour phenomena and not being programmed to consider complex foundations. Less expensive optimisations, such as dynamic or wide-graded alternatives, are not fully developed or studied at the same level of knowledge, nor have they addressed extensively complex foundations, wave, tidal, and current energy converters, and hybrid structures.
- Absence of access to data, result discussions, reports, and information *in situ*, which are retained by stakeholders, due to confidential policies, has a harmful effect on the development or optimisation of (new) scour protection design formulas.

- Probabilistic assessment and design of scour protection can lead to probabilities of failure and associated D_{50} values that can vary significantly. Thus, it is crucial to avoid generalising the probability of failure for offshore wind farms at different locations. The literature reports very few probabilistic analyses of scour protection, and no guidelines are available despite promising results.
- Although the number of studies that have used numerical models has been increasing in recent years, the majority are concerned only with scour patterns. Scour protection numerical models, not only for monopiles but also for complex foundations, remain a vast field of study that has yet to be fully explored. Most of the models focus on the structural behaviour of bottom-fixed or floating foundations.
- A significant lack of scour protection studies has been found for complex structures, particularly tripod foundations. In the literature, most studies concern scour development and its parameters. Design formulas heavily based on monopiles are still used or adapted, even though scour behaviour, flow-field modifications, blockage effects, and loads around complex structures differ.
- Most studies regarding marine harvesting technologies focus on hydrodynamics and performance improvement over scour and protection. In the present literature, there are no studies on scour protection, and scour research considers only waves for WECs or tidal currents for TECs, missing representative marine environmental conditions.
- Scour studies in hybrid structures are scarce and almost non-existent, even with the high potential that the application of energy converters in offshore wind turbines can offer. A synergy between the two could lead to cost reductions in both sectors. The development of new energy sources will enhance the competitiveness of the renewable energy sector and help lower electricity prices.
- Knowledge gaps and a lack of reports in the literature on the combination of WECs or TECs with OWTs can lead to an increase or reduction of scour effects in the foundation.

As a final note, there is a clear absence of studies that have performed physical and numerical modelling of scour protection for complex and hybrid structures and marine harvesting technologies. Although some encouragements have been made regarding the understanding of scour development and prediction formulas on OWT complex foundations and marine energy converters, it is recognisable that the future of scour research in the offshore sector involves the necessity of identifying new and specific design formulas and countermeasures for (dynamic) scour protection for these types of structures.

3. Research Program for Offshore Hybrid Structures

3.1. INTRODUCTION

The experimental research conducted within the scope of this thesis aimed to produce data to investigate damage and assess the behaviour of the armour layer of a scour protection composed of rubble-mound material, designed for a variety of structures, under a combination of incident hydrodynamic conditions. The test programme aimed at providing information for the following research questions:

- Is it possible to extend dynamic protections to foundations with complex geometry or hybrid structures?
- What is the influence of a WEC on the hydrodynamics that determines the protection's failure?
- Is it possible to provide a design tool that enables the analysis of the damage number for hybrid structures?
- What are the failure limits when using different approaches from the ones identified in the literature?

As seen in Chapter 2, there is limited information regarding the development and optimisation of scour protections for complex and hybrid OWT structures. Therefore, this work aims to help reduce these knowledge gaps. Scour metrics, such as the S/D , S_{3D} , KC_{tot} , MOB_{top} , wave transmission coefficient (K_T), wave reduction coefficient (K_{Red}), and alternative metrics such as the damage increase ratio ($\Delta S_{3D}/n_s$), damage ratio (S_{3D}/n_s) and the scour depth to protection thickness ratio (S/t_s) were measured in most of the small-scale tests. A reduced set of large-scale tests, specifically designed to investigate the converter's true influence on the protection behaviour, was conducted. This involved a more in-depth analysis of the performance and influence of the converter within the hybrid structure.

3.2. EXPERIMENTAL FACILITIES

The experimental work was carried out in the small-scale wave-current flume, Figure 25, of the Hydraulics Laboratory of the Hydraulics, Water Resources, and Environmental Division (LH-SHRHA) in the Faculty of Engineering of the University of Porto – FEUP (Portugal), and in the Large Wave Flume, Figure 26, of the O.H. Hinsdale Wave Research Laboratory (HWRL) in the Oregon State University – OSU (United States of America).

The first infrastructure is 29 m long, 1 m wide, and 1 m deep, fed by a constant head reservoir, utilising two intake pipelines (3 m above the flume). Originally, the flume was only suitable for experimental studies using steady currents. To produce waves and currents, some modifications were performed, Chambel (2019), which included the installation of a piston-type wavemaker at the upstream side of the

flume, for a maximum water depth of 0.7 m, with the potential to reproduce waves with 0.25 m. On the downstream side, the new passive wave absorption system (PWAS) was designed and implemented by Miranda *et al.* (2023) and Chambel *et al.* (2023a), thereby maintaining reflections below the recommended 15% (Frostick *et al.*, 2011).

The HWRL flume is 104 m long, 3.7 m wide, and 4.6 m deep. At one end, it features a piston-type hydraulic actuator assembly that serves as a wavemaker, allowing the reproduction of waves with periods ranging from 0.8 to 12+ seconds and a maximum wave height of 1.7 m, for a maximum water depth of 2.7 m. At the other end, there is a movable, adjustable beach with a 1:12 slope. This beach dissipates incident wave energy and controls reflections from the flume wall.

Both wavemakers can generate several types of waves, namely long-crested irregular waves with different wave spectra (JONSWAP, Pierson-Moskowitz, and others), regular waves, and solitary waves, to simulate Tsunamis. Both generation systems can actively absorb reflections through integrated systems in the paddles and the control systems. Data acquisition and wave generation control systems are operated from a control room.

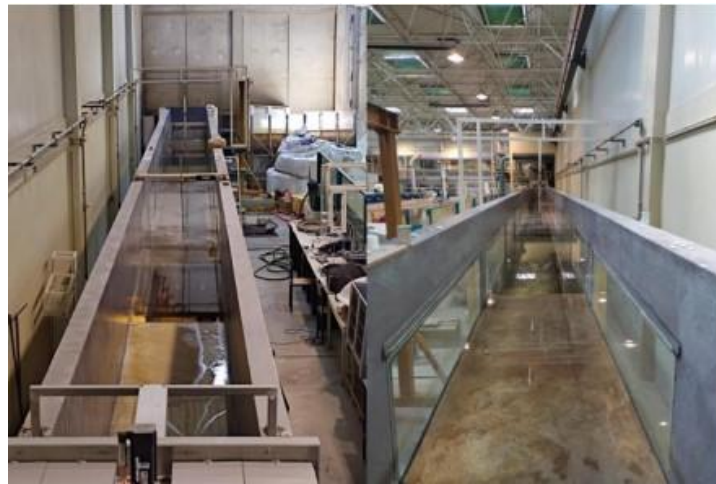


Figure 25 – LH-SHRHA's wave flume at FEUP.

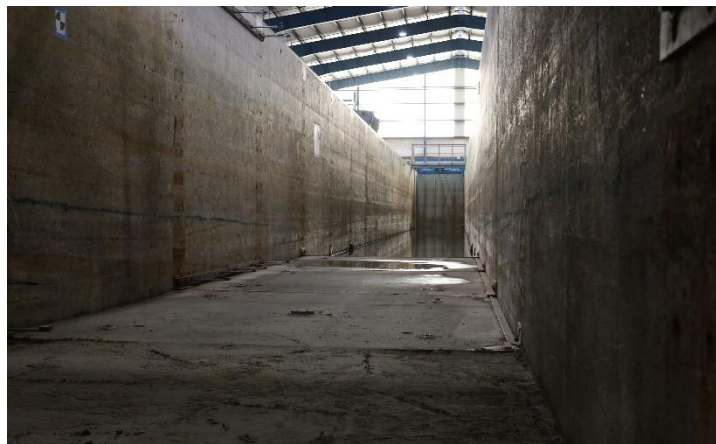


Figure 26 - O.H. Hinsdale Wave Research Laboratory's large wave flume (HWRL).

3.3. GEOMETRIC SCALE

For the physical model testing in both facilities, to set the proper geometric scale some considerations were taken: real case dimensions, knowledge of the flume dimensions, wavemaker limitations (maximum significant wave height and peak wave period versus water depth), selection of the physical processes that need to be simulated, and attention to scale effects that might exist and effect the experimental stage. A 1:50 geometric scale was selected for the small-scale experimental stage, while a 1:25 scale was chosen for the large-scale tests.

To properly simulate the hydrodynamic conditions (wave and currents), the Froude number – a number that conserves gravity effects – and the Reynolds number – a number that conserves viscous effects – must be preserved. However, when preserving the geometric length scale of one, it is not possible to scale both correctly. For scour protection models, to preserve as much as possible the hydrodynamic conditions, the Froude similitude law is adopted over the Reynolds similitude law. For scour protection models, under waves and currents, inaccurate scaling of Re can be mitigated for $Re \geq 1 \times 10^4$, as the flow regime tends to be turbulent and viscous effects can be neglected (Fazeres-Ferradosa, 2018a; Frostick *et al.*, 2011). Overall, scale effects due to the inaccurate scaling of Re can be restrained for $10^3 < Re < 10^5$ (Sumer *et al.*, 1992). Considering $Re_D = \frac{(U_c + U_m) \cdot D}{\nu}$, where ν represents the kinematic viscosity:

- For the small-scale tests in (hybrid) monopile tests, the Re_D was kept between 2.1×10^4 and 3.2×10^4 , and for the (hybrid) jacket tests, the Re_D was kept between 4.7×10^3 and 7.3×10^3 ;
- For the large-scale tests, the Re_D was kept around 6.4×10^4 .

Other numbers that must be preserved for scour protection are the KC number, which represents how the wave flow interacts with the structure and is involved in the live-bed scour regime, and the Shields parameter, which is engaged in the clear-water scour regime. However, the Froude scaling preserves both scour regimes and maintains similitude in the equilibrium scour depth (Frostick *et al.*, 2011).

3.4. PHYSICAL MODEL LAYOUT

3.4.1. SMALL-SCALE TESTS

In the small-scale experimental tests, the scour protection (Figure 27) used for the monopile tests was based on the work of De Vos (2008), De Vos *et al.* (2011), and De Vos *et al.* (2012), which involved a circular-shaped, uniform-thickness protection. A summary of the main characteristics of all test articles and materials required for the tests is presented in Table 12.

Table 12 – Characteristics for small-scale (hybrid) monopile model.

Foundation	D_p (m)	D_{n50} (mm)	Length	Thickness	Material	ρ_s (kg/m ³)	Shape
Monopile	0.11	-	-	-	Acrylic Glass	1180	Circular
Scour Protection	-	3.969	$5D_p$	$2.5D_{n50}$	Rubble mound	2666	Circular
Sediments	-	0.215 (d_{50} value)	-	-	Sand	2590	-

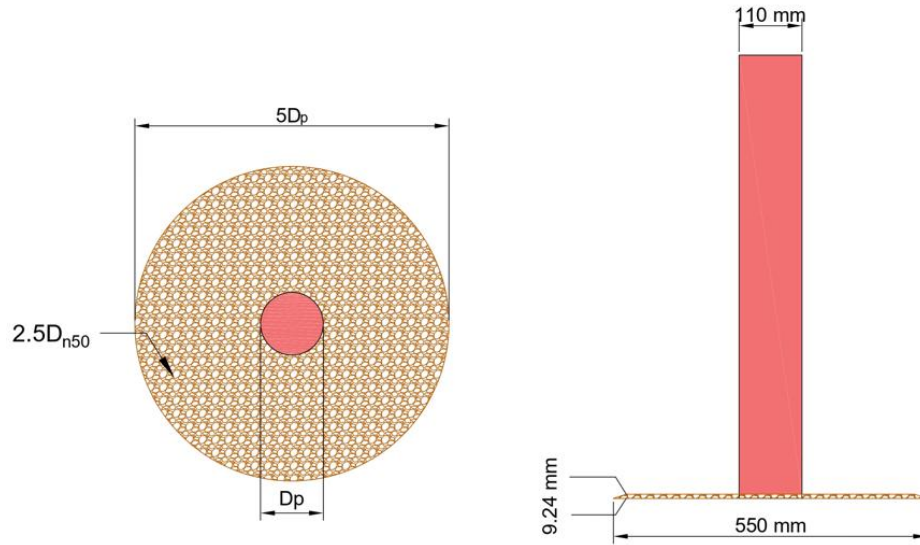


Figure 27 – Monopile physical model scheme (geometric scale 1:50).

For the jacket foundation model, a 4-legged jacket (Figure 28) was scaled based on the one used by Welzel (2021). The scour protection (Figure 29) was designed and constructed around the foundation based on scour patterns and the scour-depth equation of Welzel *et al.* (2019b, 2020), and on results reported by Sarmiento *et al.* (2021):

- Maximum scour in the vicinity of an area equal to 1.25 times the structure's footprint area (Welzel *et al.*, 2019b, 2020).
- Maximum scour depth around a jacket leg in the order of $3D_{50}$ to $5D_{50}$ registered approximately $0.5D$ from the edge of the jacket leg (Sarmiento *et al.*, 2021).

Therefore, it was decided to construct a square-shaped protection with varying thickness and a spatial coverage equal to 1.25 times the foundation's footprint. A summary of the main characteristics of all test articles and materials required for the jacket tests is presented in Table 13.

Table 13 – Characteristics for small-scale (hybrid) jacket model.

Foundation	D_{jacket} (m)	D_{n50} (mm)	Dimensions	Thickness	Material	ρ_s (kg/m ³)	Shape
Jacket	0.025	-	330 mm (width)	-	Stainless steel	8000	Square
Scour Protection	-	3.696	1.25 times the foundation footprint area	$5D_{n50}$ (piles) $3D_{n50}$ (other areas)	Rubble mound	2666	Square
Sediments	-	0.215 (d_{50} value)	-	-	Sand	2590	-

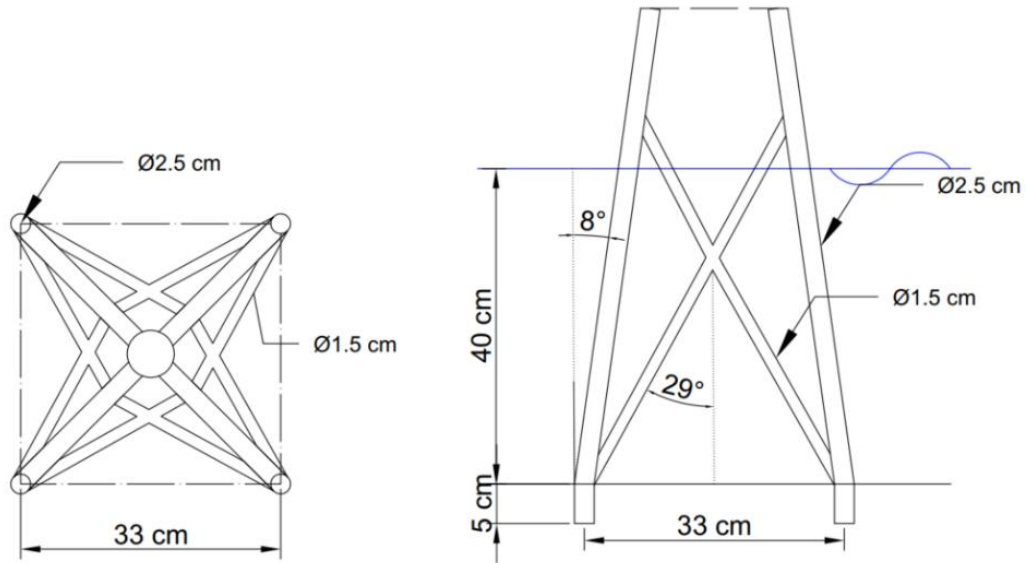


Figure 28 – Jacket physical model scheme (geometric scale of 1:50).

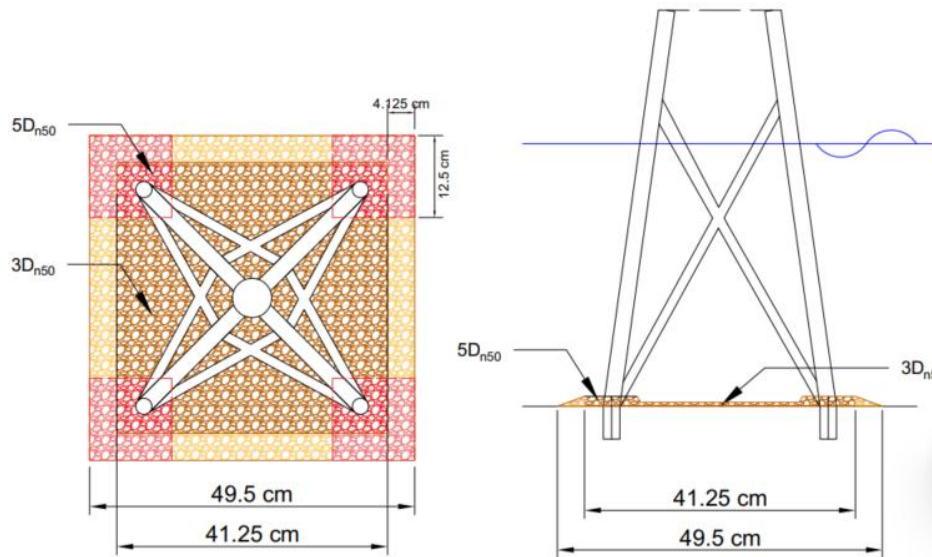


Figure 29 – Jacket scour protection model scheme (geometric scale: 1:50).

Regarding the WEC used to test the hybrid structure, it was decided to adapt, simplify, and scale down the FOSWEC v2 device developed at OSU (Bosma *et al.*, 2016; Coe *et al.*, 2020; Ruehl *et al.*, 2019). The adapted model (Figure 30) comprises two flaps hinged to a central platform, with a simplified spring system that limits the flaps' pitch to a maximum motion angle of $\pm 25^\circ$ as in Ruehl *et al.* (2019).

The simplification and substitution of a fully functional PTO system were made because the primary goal was to assess the device's initial impact on the amplification of flow patterns and, consequently, its influence on scour protection damage, rather than evaluating the converter's performance/efficiency. The model was fixed with cantilevers and positioned with a tip clearance of 15 cm above the sediment bed, transforming it from a floating device into a fixed OSWEC.

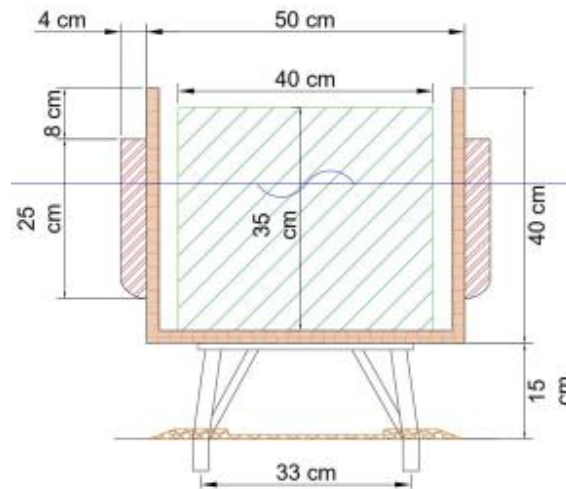


Figure 30 - WEC model designed for the experimental tests (geometric scale: 1:50).



Figure 31 – Hybrid jacket model (small-scale test).

3.4.2. LARGE-SCALE TESTS

For experimental testing at the HLWF, a layout similar to that used for the small-scale monopile tests was planned. However, small updates were implemented, considering not only the facilities' infrastructure but also the results of the small-scale test. Two different scour protections were designed:

- A static protection, to prevent excessive damage rates.
- A dynamic protection, designed to provide a certain degree of mobility.

However, based on the results of the small-scale tests, which showed severe damage in the hybrid configurations, the protection extent was increased to cover the entire footprint beneath the converter, and the thickness was reinforced. The intended purpose was to explore the feasibility and performance of two different scour protection systems under realistic wave-hydrodynamic conditions and WEC-

induced motions, applicable to different MRE devices and structures. A summary of the main characteristics of all test articles and materials required for the tests is presented in Table 14.

The FOSWEC, currently available at HWRL, is a floating energy converter, developed by Sandia National Laboratories and Oregon State University's HWRL, consisting of a dual-flap surge-type WEC attached to a central support frame and moored via tethers to maintain position under various hydrodynamic conditions (Figure 32). The oscillatory motion of the flaps converts wave-induced motion/forces into mechanical energy via a PTO system. However, fixing the device to the monopile will convert it into an OSWEC, specifically a hybrid OSWEC structure. This enables understanding of how waves interact with complex structures, while enhancing sediment transport/erosion

By measuring hydrodynamic and morphodynamic parameters, the large-scale test results will clarify how WEC-induced motion modifies scour, how it will influence the efficiency of both scour protection systems, and how flow patterns, such as downflow, horseshoe, and lee-wake vortices, that are the primary drivers of scour, are enhanced.

The aim is that the results and discussions provided may contribute to the development of cost-effective and reliable scour protections in the future. The outcomes will:

- Extending the methodology proposed by Fazeres-Ferradosa *et al.* (2020) to evaluate the S_{3D} (damage number) to different MRE devices/structures.
- Provide large-scale validation data that can be used in the future for the calibration of numerical models.
- Compare and assess the behaviour of static and dynamic scour protection for a non-hybrid and a hybrid structure/device, so new design approaches can be developed in the future for a large variety of MRE structures/devices.

The expectation is that the results align with the strategic objectives by contributing to the sustainable expansion of renewable energy, supporting reductions in LCoE, and advancing/improving long-term structural resilience in the MRE sector.

Table 14 – Scour protection characteristics for large-scale (hybrid) monopile tests.

Foundation	D_p (m)	D_{n50} (mm)	Length	Thickness	Material	ρ_s (kg/m ³)	Shape
Monopile	0.22	-	-	-	PVC	1450 (PVC)	Circular
Hybrid Monopile	0.22	-	-	-	Stainless steel	8000 (Stainless Steel)	Circular
Static Protection	-	32	$10D_p$	5 cm ($1.56D_{n50}$)	Rubble mound	2800	Circular
Dynamic Protection	-	8	$10D_p$	5 cm ($6.25D_{n50}$)	Rubble mound	2700	Circular
Sediments	-	0.200 (d_{50} value)	-	-	Sand	2670	-



Figure 32 – FOSWEC updated version (Oregon State University).

3.5. DATA ACQUISITION AND INSTRUMENTATION

Data acquisition and instrumentation were deployed along and near the test articles to capture the hydrodynamic conditions. Data recording was fully synchronised and sampled, ensuring a proper and detailed description of physical processes. Wave gauges were regularly calibrated, and their measurement range is tailored to the project's needs. Acoustic Doppler Velocimetry (ADV) devices were used to measure current velocities. All data was recorded, handled, post-processed, and converted to physical units. Details on incident wave conditions at different locations, along with measured orbital velocities, were used to correlate with scour response, expressed as damage level and scour depth. Laser-scanning survey measurements were used to assess the morphological evolution of the scour protection. Regarding the large-scale testing, the converter's own data acquisition system (DAQ) was enabled to provide a time series of the flap's position and corresponding torque. The angular velocity of the flap multiplied by the torque on the shaft yields the time series of mechanical power, a proxy for the power absorbed by the device.

3.5.1. WAVE GAUGES

For surface water elevation measurements, resistive wave gauges (WG) were installed along both flumes, as shown in Figure 33 and Figure 34. The gauges will measure the water-free surface elevation to measure the wave time series near the model setup. A daily calibration will be performed whenever the water level changes. Wave gauge data is recorded by the HR Wallingford DAQ system at FEUP and the HWRL DAQ system at OSU, with a sample frequency typically set to 100Hz. Mean voltage estimates are then converted by a linear least-squares fit between the observed wave gauge voltages and the calibrated water depth observations. The following wav gauge disposition was used for:

- **Small-scale testing:** a single wave gauge placed near the wave paddle to measure the wave conditions. Two wave gauges were placed on the offshore side of the model to measure the local wave conditions, and one on the onshore side, to assess the effects of the WEC on the transmission and reduction coefficient.

- **Large-scale testing:** five WGs were placed after the approach slab to estimate incident and reflected wave conditions. One WG was placed on the offshore side near the model to measure local wave conditions, and another on the onshore side to assess the effects of the WEC on the transmission and reduction coefficients.

The U_m was estimated using a MATLAB (v.R2022b) routine developed by Wiberg and Sherwood (2008), which is necessary to accurately predict the S_{3D} value.

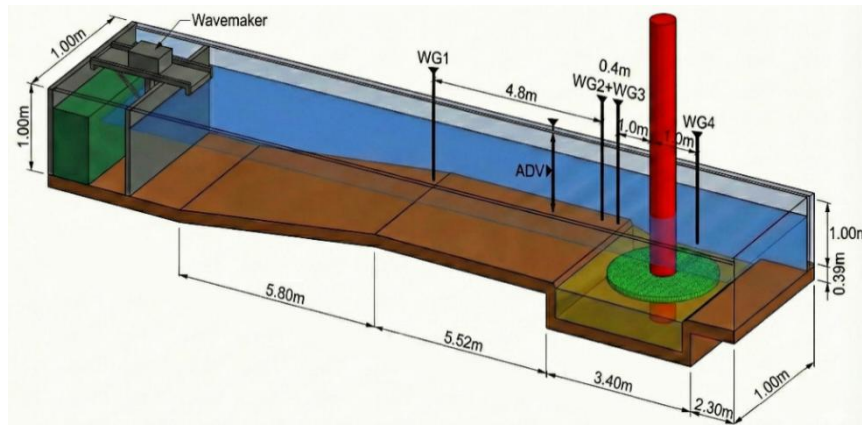


Figure 33 – Representation of the physical model setup used for the small-scale tests at FEUP.

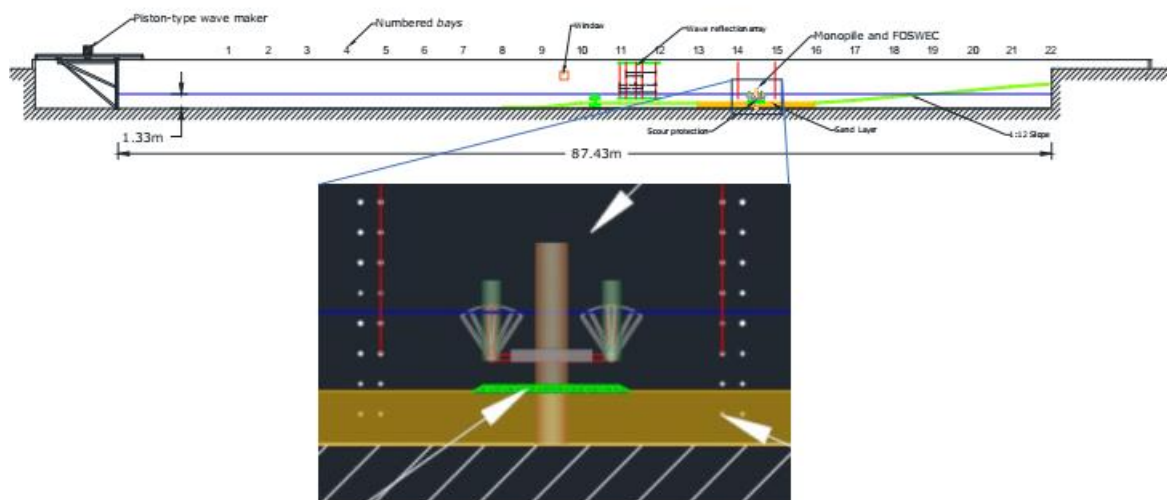


Figure 34 – Longitudinal cross-section of the HWRL's flume with the hybrid structure model shown in detail.

3.5.2. ACOUSTIC DOPPLER VELOCIMETER (ADV)

Flow measurements were taken using the Nortek Vectrino-II ADVs (Figure 35), which were deployed closer to the bottom to capture the velocities responsible for the scour. The ADVs were used at a sampling rate of 100 Hz, applying the Doppler effect to compute velocity vectors at a single point 5 cm from the probe. The locations were chosen to avoid signal interference from the bed ripple migration and to capture undisturbed flow conditions (Figure 33 and Figure 34).

For the small-scale tests, only one ADV was used due to spatial constraints. Additional sensors were excluded from the immediate vicinity (side/rear) and from inside the structure to avoid blockage effects

that could induce significant flow disturbances and signal interference with the downstream wave gauge. For the large-scale tests, three ADVs were placed along the flume: one closer to the offshore WG, one between the offshore and onshore WG, and one closer to the onshore WG. An additional ADV was placed closer to the left side of the model to compare the results with the intermediate ADV and estimate the flow enhancement induced by the WEC motion.



Figure 35 – Nortek Vectrino-II ADV (Nortek).

3.5.3. LASER SCANNER

To capture the full evolution of the sediment bed and the scour protection, laser-scanning surveys, also known as LiDAR (Light Detection and Ranging) surveys, were conducted using a:

- FARO® Focus (points per second: 2,000,000, precision: 2 mm at 10 m, range noise: 1 mm at 10 m and 25 m) – at FEUP.
- Leica® BLK 360 (points per second: 680,000, precision: 4mm at 10 m, range noise: 0.4 mm at 10 m and 0.5 at 20 m) – at OSU.

Since Standard Infrared Laser Scanners can only operate in dry conditions, the flumes had to be drained for measurement. Laser-scanning surveys generate high-resolution 3D Digital Terrain Models (DTMs) that accurately represent erodible areas and their surroundings by capturing millions of points and mapping them to a coordinate system via markers placed across the lab. Scans were conducted before and after each experimental test, as well as for each 1000-wave train at FEUP. At OSU, scans were taken only before and after each test, with the intermediate surveys conducted using a submersible structure with a Multiple Transducer Array (MTA) ultrasonic ranging system. The advantage of the MTA is its ability to survey underwater, so no draining is necessary between intermediate wave trains. The 8 MTA sets were spaced 8 cm apart, for a total of 64 transducers. Since the scanners and MTAs' precision is smaller than the armour layer's D_{n50} , even small unit displacements and spot deformations can be reliably detected.

The DTMs were post-processed using Autodesk ReCap and CloudCompare, resulting in precise point clouds of the sediment bed and scour protection profiles. The DTMs were subsequently analysed to determine scour depth and measured damage numbers using a MATLAB (v.R2022b) routine developed to compute S_{3D} using the overlapping-circle method, as described by Fazerer-Ferradosa *et al.* (2020), for the monopile testing, and an adapted version specifically developed for the four-leg jacket with a square-shaped scour protection (Chapters 5 and 6). A more detailed description of how the overlapping-circle method was used for damage characterisation can be found in Appendix III, IV, and V (Chambel *et al.*, 2025, 2026a, 2026b).



Figure 36 – Laser scanners: Faro® Focus (left) and Leica® BLK 360.

3.6. TEST PROGRAMME

3.6.1. SMALL-SCALE TESTS

The experimental test program proposed for the scour assessment is presented in detail in Table 15 (monopiles [M] and hybrid monopiles [MH]) and in Table 16 (jackets [J] and hybrid jackets [JH]). The conditions were determined in a first phase that included a reflection analysis to determine the gain factor and verify whether the recommended 15% reflection coefficient limit was met. In the second phase, a dynamically designed scour protection was applied to a monopile and a hybrid monopile. Finally, the third phase consisted of the experimental testing of the same dynamic scour protection configuration applied to a jacket and a hybrid jacket structure. All tests considered different hydrodynamic conditions: irregular waves with currents in the same direction (WC), irregular waves-only (WI), and regular waves-only (WR). The considered irregular sea states were defined by a JONSWAP (Joint North Sea Wave Project) spectrum with a peak enhancement factor, γ , of 3.3, representative of the North Sea conditions. Each test condition was run for 3000 waves.

Table 15 – Experimental small-scale test campaign (monopile and hybrid monopile) – prototype values.

Test	Foundation	Scour Protection	WEC	d (m)	H_s (m)	T_p (s)	U_c (m/s)	U_m (m/s)	U_{cw}	KC	S_{3D} (predicted)
M_WC_7	Monopile	Riprap	-	20	3.50	10.00	1.11	0.57	0.64	1.03	0.08
M_WC_11					5.50	12.00	1.11	1.01	0.56	2.21	0.63
M_WC_15.5					7.75	14.00	0.35	1.29	0.64	3.29	1.79
M_WI_14					7.00	16.00	-	1.47	0.00	4.28	3.43
MH_WR_14					7.00 (Reg.)						
MH_WC_7		Riprap	OSWEC	20	3.50	10.00	1.11	0.57	0.64	1.03	0.08
MH_WC_11					5.50	12.00	1.11	1.01	0.56	2.21	0.63
MH_WC_15.5					7.75	14.00	0.35	1.29	0.64	3.29	1.79
MH_WI_14					7.00	16.00	-	1.47	0.00	4.28	3.43
MH_WR_14					7.00 (Reg.)						

Table 16 – Experimental small-scale test campaign (jacket and hybrid jacket) – prototype values.

Test	Foundation	Scour Protection	WEC	d (m)	H_s (m)	T_p (s)	U_c (m/s)	U_m (m/s)	U_{cw}	KC	S_{3D} (predicted)
J_WC_7	Jacket	Riprap	-	20	3.50	10.00	1.11	0.57	0.64	4.52	0.08
J_WC_11					5.50	12.00	1.11	1.01	0.56	9.71	0.63
J_WC_15.5					7.75	14.00	0.35	1.29	0.64	14.49	1.79
J_WI_14					7.00	16.00	-	1.47	0.00	18.83	3.43
J_WR_14					7.00 (Reg.)						
JH_WC_7		Riprap	OSWEC	20	3.50	10.00	1.11	0.57	0.64	4.52	0.08
JH_WC_11					5.50	12.00	1.11	1.01	0.56	9.71	0.63
JH_WC_15.5					7.75	14.00	0.35	1.29	0.64	14.49	1.79
JH_WI_14					7.00	16.00	-	1.47	0.00	18.83	3.43
JH_WR_14					7.00 (Reg.)						

3.6.2. LARGE-SCALE TESTS

For the large-scale test program, the geometric scale selection boiled down to a compromise between the largest dimensions to avoid scale effects, and the reduction of the scale to minimise side wall effects. A geometric scale of 1:25 was chosen to test protected monopiles (Figure 37) and hybrid structures (Figure 38) under large waves, while minimising sediment-scale effects. The HWRL's flume only allows the reproduction of wave-only conditions. Nonetheless, due to the capabilities of its infrastructure and wavemaker, it can reproduce higher wave conditions than those at FEUP's flume. Therefore, the hydrodynamic conditions were selected to represent a severe case scenario (Table 16). The proposed foreshore bathymetry considers a deeper portion for wave generation, a shoaling slope and a horizontal platform representing the seabed (Figure 34). In a portion of the horizontal platform, a sediment pit was installed, using natural sand obtained from the coast near OSU. The initial conditions for the monopiles required calibration to accommodate the WEC's geometric and operational constraints. Therefore, for the hybrid structure, a deeper water depth was required. To preserve hydrodynamic equivalence, the wave height was also recalibrated to maintain identical near-bed orbital velocities and KC numbers, ensuring that the governing flow regimes and scour mechanisms remained comparable. Six different setups/cases were tested in the following sequence:

- **Case MS:** Monopile with static scour protection.
- **Case HFS:** Hybrid structure (monopile + converter) with fixed flaps and static scour protection.
- **Case HMS:** Hybrid structure (monopile + converter) with moving flaps and static scour protection.
- **Case MD:** Monopile with dynamic scour protection.
- **Case HFD:** Hybrid structure (monopile + converter) with fixed flaps and dynamic scour protection.
- **Case HMD:** Hybrid structure (monopile + converter) with moving flaps and dynamic scour protection.

The tests were performed using irregular waves following a JONSWAP spectrum with a peak enhancement factor (γ) of 3.3, run for 3000 waves. The experimental test plan considered the subsequent variables:

Table 17 – Experimental large-scale test campaign – prototype values.

Test ID	Foundation	Scour Protection	Energy Converter	d (m)	H _s (m)	T _p (s)	U _m (m/s)	U _{cw}	KC	S _{3D} (predicted)
MS	Monopile	Static	-	20	10	16	0.42	0.00	6.09	0.53
HFS		D_{n50} : 0.80 m	OSWEC	30	13.25					
HMS										
MD	D_p : 5.5 m	Dynamic	-	20	10	16	0.42	0.00	6.09	8.54
HFD		D_{n50} : 0.20 m	OSWEC	30	13.25					
HMD										



Figure 37 – Large-scale scour protection model for a monopile: static protection (left), dynamic protection (right).



Figure 38 – Large-scale scour protection model for the hybrid structure: static protection (left), dynamic protection (right).

3.7. TEST PROCEDURE

For a successful experimental campaign, it was necessary to follow the same procedures before, during, and after each test. This way, it can be ensured that each test is performed under the same conditions. The experimental stage will follow the subsequent steps:

1. Perform an initial measurement (DTM) of the seabed and scour protection bathymetry to use as a reference.
2. Fill the wave flume slowly with water.
3. Calibrate the wave gauges.
4. Set up the software for the corresponding experimental test conditions.
5. Start running the waves for the selected experimental test.
6. Measure the currents (ADV) and waves (DAQ system + wave gauges).
7. Wait until the test is finished.
8. Drain the wave flume slowly.
9. Perform an intermediate or final measurement of the bathymetry (in case of intermediate measure, return to the 2nd step) + visual monitoring of the experiment.
10. Check all the DTMs from the photogrammetry and the measurements from the wave gauges.
11. Perform the damage number measurements for all the profiles.
12. Flatten the sand and rebuild the scour protection before the next test.

4. Experimental Study of Scour Protections for Hybrid Monopiles

4.1. INTRODUCTION

The experimental study described in Chapter 3 was used to compare the performance of riprap scour protection applied to both a monopile and a hybrid monopile structure. By designing scour protection in accordance with current literature, this chapter's main goal is to evaluate the adequacy of existing design formulas by comparing measured results with predictive values. To ensure precise damage quantification, the overlapping-circle method is applied. The work advances the state of the art by presenting one of the first physical model tests of protected hybrid monopiles to assess the device's influence on the main scour-induced flow mechanisms. The hybrid configuration was achieved by coupling an OSWEC to the structure. The main findings were published in Chambel *et al.* (2025) and are presented in this chapter.

4.2. DAMAGE NUMBER

For all tests, the representative damage number was computed by applying the overlapping-circle method introduced by Fazeres-Ferradosa *et al.* (2020), using as reference inputs a sub-area (A_{sub}) equal to $4D_{n50}^2$ and an overlapping distance of 50%, thus enabling an objective quantification of the scour protection damage under each test condition. The overlapping method provided high-resolution representations of scour patterns and high accuracy in the S_{3D} -measured values and distribution (see Figures in Appendix III). Table 18 summarises all the measured conditions. The U_{cw} values differentiate the three wave-dominated tests ($U_{cw} < 0.44$) from the current-dominated tests ($U_{cw} > 0.44$), Chen and Li (2018). As expected, S_{3D} generally correlates strongly with the intensity of the hydrodynamic load. Under low-energy conditions, the maximum S_{3D} measured values were lower and increased with higher wave heights. Additionally, when comparing the results of the wave-only tests (M_WI vs. M_WR and MH_WI vs. MH_WR), the S_{3D} values were slightly higher when using regular waves, aligning with the findings of a study conducted on rubble mound structures (Sumer and Fredsøe, 2000), with these differences attributed to the fact that the root mean square (H_{rms}) value for irregular waves tends to be smaller than the wave height for regular waves.

For the monopile tests, the scour protections showed lower damage rates across all hydrodynamic conditions than their hybrid counterparts (Table 18 and Figures in Appendix III), where highly pronounced scour deformations were observed under similar conditions. In some instances, nearly double or triple the damage levels observed in the corresponding monopile tests were recorded, consistent with intense sediment erosion, armour-layer washout, and significant seabed sinking beneath the filter layer (Figure 39).

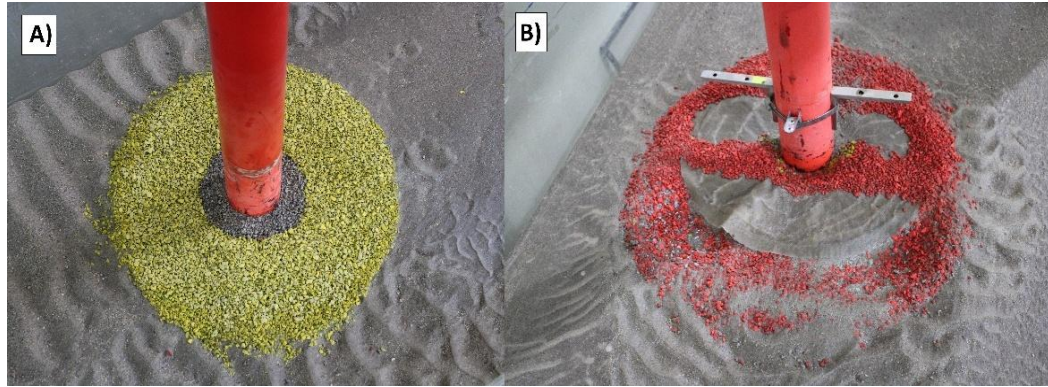


Figure 39 – Damage comparison between the test at 1000 waves: (A) monopile test M_WR_14 and (B) hybrid monopile test MH_WR_14 (stopped due to armour layer failure).

Table 18 – Experimental measured conditions for monopile and hybrid monopile tests (model values).

Test	No. of Waves	H_{m0} [m]	T_p [s]	U_m [m/s]	U_c [m/s]	U_{cw}	S_{3D} (Predicted)	S_{3D} (Measured)	Visual Classification
M_WC_7_1000	1000	0.072	1.471	0.085	0.157	0.65	0.06	1.43	Slightly Dynamic (all 3000 waves)
M_WC_7_2000	1000	0.073	1.471	0.086	0.157	0.65	0.07	2.11	
M_WC_7_3000	1000	0.073	1.471	0.086	0.157	0.64	0.08	1.95	
M_WC_11_1000	1000	0.100	1.613	0.126	0.156	0.55	0.48	1.73	Dynamic (all 3000 waves)
M_WC_11_2000	1000	0.104	1.613	0.131	0.158	0.55	0.57	1.63	
M_WC_11_3000	1000	0.111	1.613	0.140	0.157	0.53	0.63	1.83	
M_WC_15.5_1000	1000	0.155	2.083	0.223	0.048	0.18	1.79	2.87	Failure
M_WI_14_1000	1000	0.136	2.174	0.199			2.63	2.77	Dynamic (Almost Failure, all 3000 waves)
M_WI_14_2000	1000	0.136	2.174	0.199	-	0.00	3.11	3.08	
M_WI_14_3000	1000	0.136	2.174	0.199			3.43	3.08	
M_WR_14_1000	1000	0.142	2.222	0.209			2.63	3.18	Failure (1000 waves)
M_WR_14_2000	1000	0.143	2.174	0.209	-	0.00	3.11	3.30	
M_WR_14_3000	1000	0.143	2.174	0.209			3.43	3.21	
MH_WC_7_1000	1000	0.074	1.299	0.078	0.156	0.67	0.06	1.97	Failure (2000 waves)
MH_WC_7_2000	1000	0.071	1.471	0.084	0.155	0.65	0.07	3.25	
MH_WC_7_3000	1000	0.070	1.471	0.083	0.157	0.65	0.08	2.86	
MH_WC_11_1000	1000	0.110	1.613	0.139	0.157	0.53	0.48	5.38	Failure
MH_WC_15.5_1000	1000	0.156	1.961	0.219	0.051	0.19	1.79	9.81	Failure
MH_WI_14_1000	1000	0.138	2.273	0.205	-	0.00	2.63	7.28	Failure
MH_WR_14_1000	1000	0.137	2.273	0.203	-	0.00	2.63	8.55	Failure

In most hybrid-structure tests, failure occurred within the first 1000 waves. The only hybrid monopile test that provided scour protection during some of the initial enhanced flow patterns was MH_WC_7, which withstood 2000 waves. The flow patterns responsible for scour around monopiles are well documented (Petersen *et al.*, 2015). However, based on the results obtained for the hybrid structure, it is reasonable to assume that some of the main mechanisms responsible for scour were amplified. Due to the oscillatory movement of the paddles, the downflow on the front side of the foundation was the

flow pattern causing most of the damage. Conversely, on the leeside, the movement of the downstream paddle increased the intensity of the lee-wake and counter-rotating vortices. Furthermore, due to the WEC's dimensions, the approaching flow conditions increase streamline contractions around and beneath the device, further contributing to the overall impact. In contrast, monopiles remained intact under mild conditions, such as M_WC_7 and M_WC_11, demonstrating dynamic behaviour throughout the 3000 waves. For more severe conditions, protection failed for M_WC_15.5 and M_WR_14 within the first 1000 waves. Although the regular wave-only test failed during the initial wave train, it was continued for comparison with the irregular wave test. The same approach was taken for the hybrid test MH_WC_7, where failure occurred before reaching the 3000-wave limit, but a final wave train was conducted for comparison with the non-hybrid version. Regarding the M_WI test, the $S_{3D}=3.08$ value suggested that the scour protection had failed. Yet, upon visual assessment of damage and comparing it to the damage distribution (Figure 40), no distinctive filter exposure was observed near the pile, despite some intense movement of the armour layer units. Consequently, the protection was on the borderline between dynamic behaviour and failure.

A significant advantage of dynamic scour protection is its ability to reshape and recover from a certain level of damage, facilitated by the movement allowed among the armour layer units (den Boon *et al.*, 2004). This capacity was empirically observed during the experimental tests, particularly in tests M_WC_7_2000 to M_WC_7_3000. Additionally, this feature was evident in a protection that failed, from MH_WC_7_2000 to MH_WC_7_3000, where partial recovery from substantial damage was observed, measured as an S_{3D} reduction from 3.25 to 2.86. Although both scenarios involved filter exposures, a subset of scour holes identified after exposure to a 2000-wave train was filled during exposure to a 3000-wave train. This backfilling came from armour layer units that had been displaced earlier (Figure 41), indicating a potential for recovery under mild conditions. Such observations raise an important question about whether scour protections can recover and regain dynamic stability after failure.

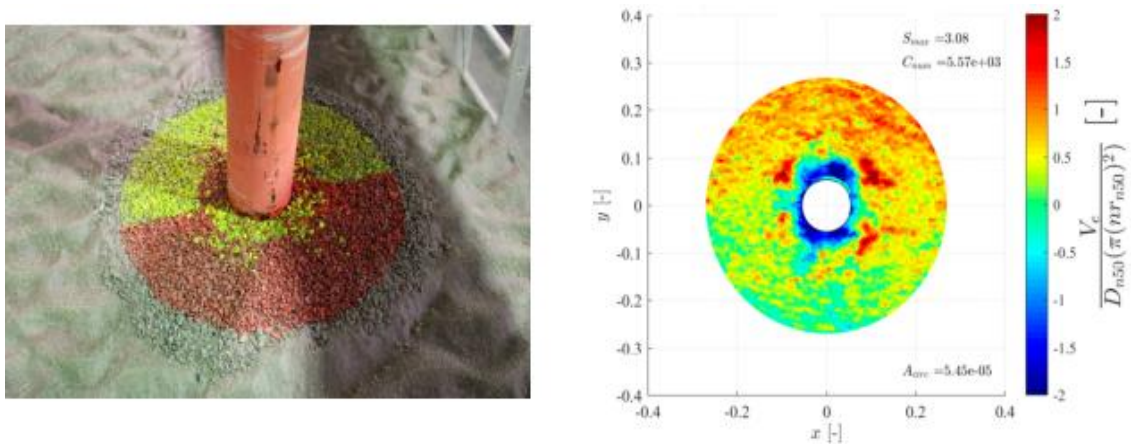


Figure 40 – M_WI_14 (3000 waves) result: visual register (left) vs. S_{3D} distribution (right).

A discrepancy appears when comparing the S_{3D} measured values with those predicted by Equation (4) formula (Table 18). Generally, the formula underestimates scour for the tested conditions. This issue is magnified when dealing with a hybrid structure. The formula underestimates actual damage, suggesting that it should include additional nonlinear factors present in more complex or hybrid systems. However,

this underestimation also results from methodological differences in how damage is measured between the approach developed by De Vos *et al.* (2012) and that of Fazeres-Ferradosa *et al.* (2020). The methodology established by De Vos *et al.* (2012) uses fixed sub-areas equivalent to the monopile cross-section and averages the scour depth over larger areas. Additionally, it does not consider the thickness of the scour protection.

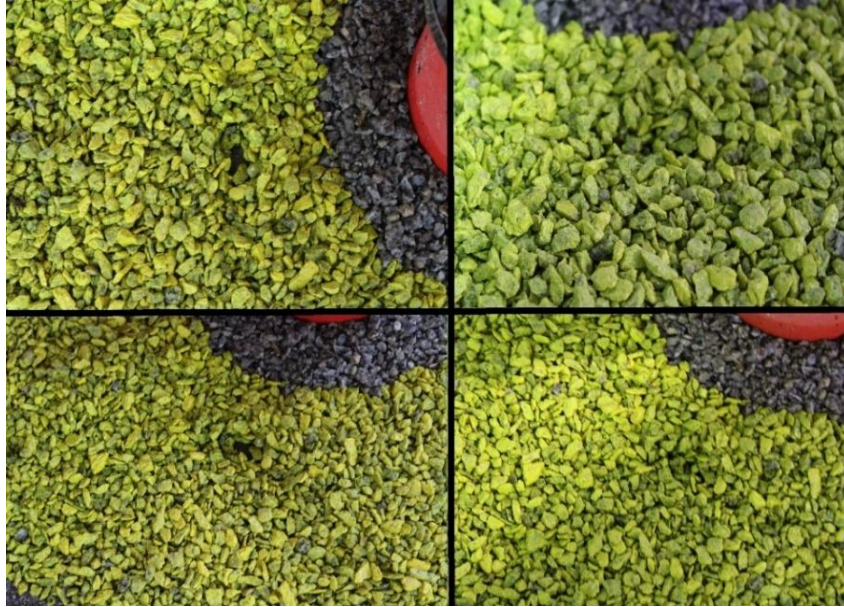


Figure 41 – Scour holes (MH_WC_7 at 2000 waves – left) and refilling (MH_WC_7 at 3000 waves – right).

Hence, if the damage number reflects the number of protection layers lost to scour as a function of D_{n50} or D_{50} , as indicated by De Vos *et al.* (2012), then an S_{3D} of 1.0 does not necessarily imply physical failure. Even dynamically stable scour protections were observed by Fazeres-Ferradosa *et al.* (2018a, 2020) for S_{3D} values greater than 1.0, up to 1.25, indicating that the reference values proposed by De Vos *et al.* (2012) can be conservative. Conversely, the approach developed by Fazeres-Ferradosa *et al.* (2020) enables the use of the failure criterion proposed by den Boon *et al.* (2004), in which the sub-area to be analysed is defined over an overlapping mesh created on the protection. Therefore, for a chosen A_{sub} , such as $4D_{n50}^2$, exposure and failure of the filter layer should at least occur when $S_{3D} \cdot D_{n50} \geq t_s$. Given this, comparing S_{3D} and thickness as a function of D_{n50} could provide more insight. Consequently, the failure threshold should not be a fixed value independent of protection thickness, like $S_{3D}=1.0$ as proposed by De Vos *et al.* (2012), but rather a range around $S_{3D}=n_s$ for $t_s=n_s \cdot D_{n50}$, accounting for some uncertainty, where n_s represents the number of rock stone size layers (De Schoessiter *et al.*, 2014).

Adopting this perspective, comparing measured damage number ($S_{3D,measured}$) values to a failure baseline of $S_{3D,failure}=2.5$, which is determined by the n_s value used during the experimental tests, allows for a clearer visual interpretation of the scour protection's behaviour as a function of the damage number measured with the overlapping method and provides a more straightforward understanding of the physical meaning of the damage number (Figure 42 to Figure 44). The static limit of $S_{3D,static}=0.25$ was maintained, as in De Vos *et al.* (2012). It is worth emphasising that for the M_WI test, the damage number values obtained indicate failure for all 3000 waves, even when $S_{3D,failure}=2.5$. This reinforces the

idea that the boundary between scour behaviour classifications should be defined within a range that accounts for a degree of uncertainty rather than a single fixed threshold.

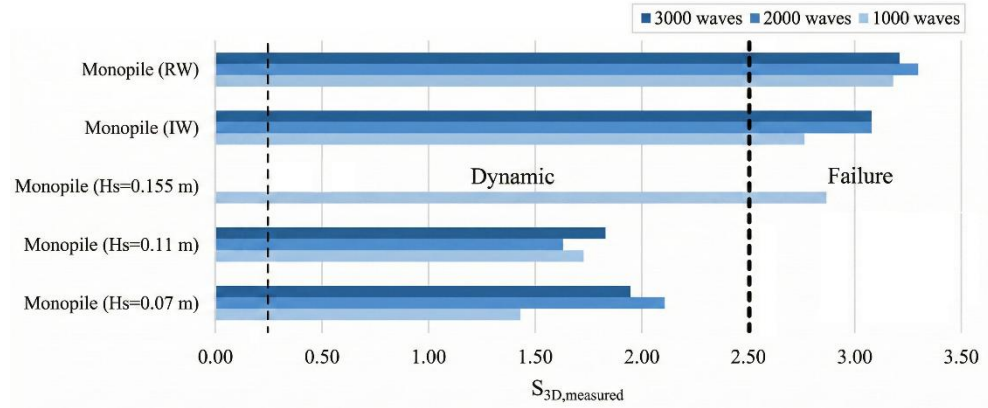


Figure 42 – $S_{3D,measured}$ vs. Stability Classification for new threshold limits based on the thickness of the scour protection (monopile tests).

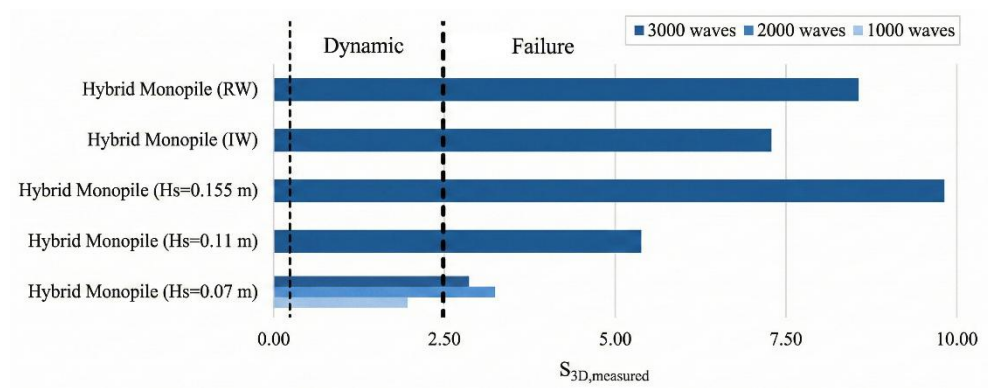


Figure 43 – $S_{3D,measured}$ vs. Stability Classification for new threshold limits based on the thickness of the scour protection (hybrid monopile tests).

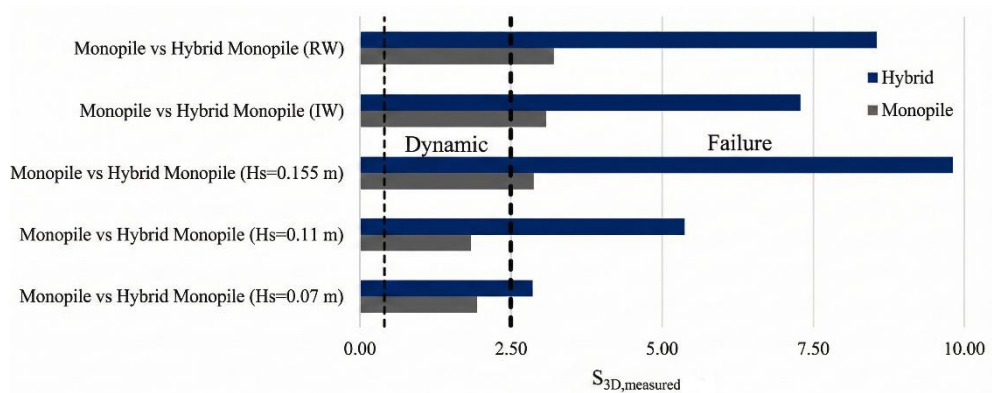


Figure 44 – Comparison of $S_{3D,measured}$ values between monopile and hybrid monopile tests.

As a side note, in some tests (M_WC_7, M_WR, and MH_WC_7), the damage number peaked around 2000 waves and then decreased slightly to 3000 waves, or remained constant, in the M_WI test series. This suggests that most damage occurs within the first 1000 waves, as noted by De Schoessiter *et al.* (2014). Afterwards, scour holes begin to fill with surrounding material, after 3000 or even 5000 waves, while additional holes may appear, indicating an equilibrium within this period.

4.3. OVERLAPPING GRID RATIO

Fazeres-Ferradosa *et al.* (2020) demonstrated that the damage number computed using their overlapping-circle method is strongly influenced by the grid ratio. However, the analysis of volumetric damage with respect to the grid ratio ($\eta_{S3D,grid}$) and its convergence was conducted only for two large-scale cases. To expand and compare their dataset with the tests performed during this study, an analysis of the maximum damage number ($S_{3D,max}$) results for each test at different $\eta_{S3D,grid}$ values was carried out. Furthermore, since the maximum damage number is valid only for a single point at the deepest part of the scour protection, a statistical study of the development of the standard deviation and the 95% percentile of the S_{3D} was carried out to examine possible convergence. The grid ratios were chosen to encompass a variety of A_{sub} values and arrangements (Figure 45), including the monopile cross section (A_{pile}) used by De Vos *et al.* (2012), $25D_{n50}^2$ (corresponding to five armour layer units), $4D_{n50}^2$ similar to the exposed failure area as in den Boon *et al.* (2004), and many others equivalent to arrangements of multiple or even single armour layer units ($nD_{n50} \times nD_{n50}$ and $nD_{n50} \times mD_{n50}$).

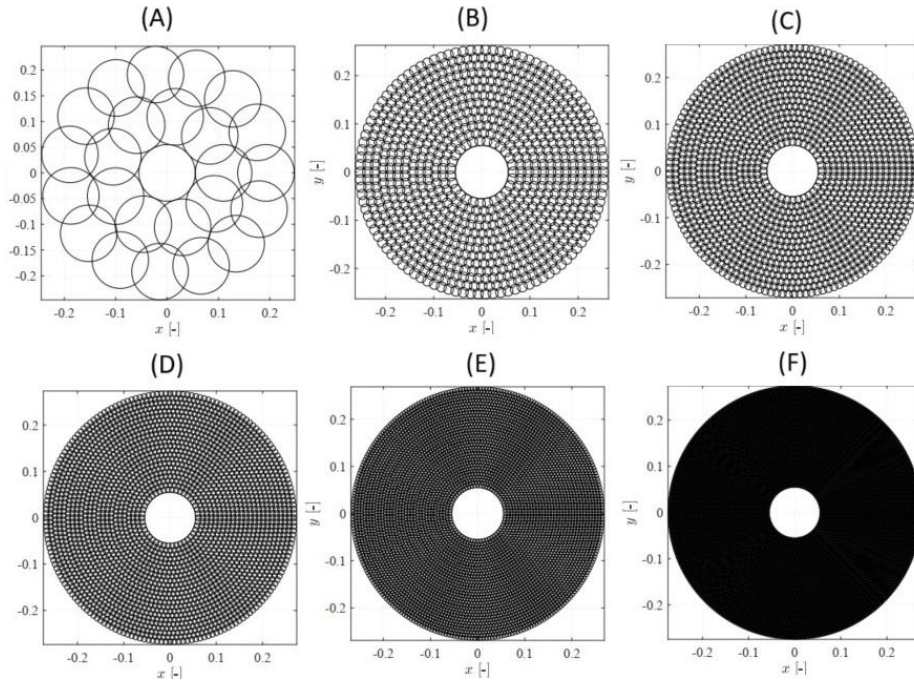


Figure 45 – Overlapping-circle arrangement for different $\eta_{S3D,grid}$ and sub-areas: (A) $\eta_{S3D,grid}=1.43 \times 10^{-3}$, $A_{sub}=A_{pile}$; (B) $\eta_{S3D,grid}=1/25$, $A_{sub}=25D_{n50}^2$; (C) $\eta_{S3D,grid}=1/16$, $A_{sub}=16D_{n50}^2$; (D) $\eta_{S3D,grid}=1/9$, $A_{sub}=9D_{n50}^2$; (E) $\eta_{S3D,grid}=1/4$, $A_{sub}=4D_{n50}^2$; (F) $\eta_{S3D,grid}=1$, $A_{sub}=D_{n50}^2$.

Varying the grid ratio changes the number of elements, significantly affecting the maximum damage number. Figure 46 shows the case for the M_WC_11_3000 tests. For higher grid ratios, meaning smaller A_{sub} and more sub-areas, the scour pattern becomes closer to the DTM representation. The figure also highlights the strong variation of outcomes for different ratios. When A_{sub} equals the monopile cross-section, the minimum number of analysed elements, the maximum damage number observed was negative, indicating sediment accretion. Conversely, when A_{sub} matches the size of a single armour layer unit (D_{n50}^2), the damage number was higher than $S_{3D, failure}=2.5$, which may be representative of a spot deformation.

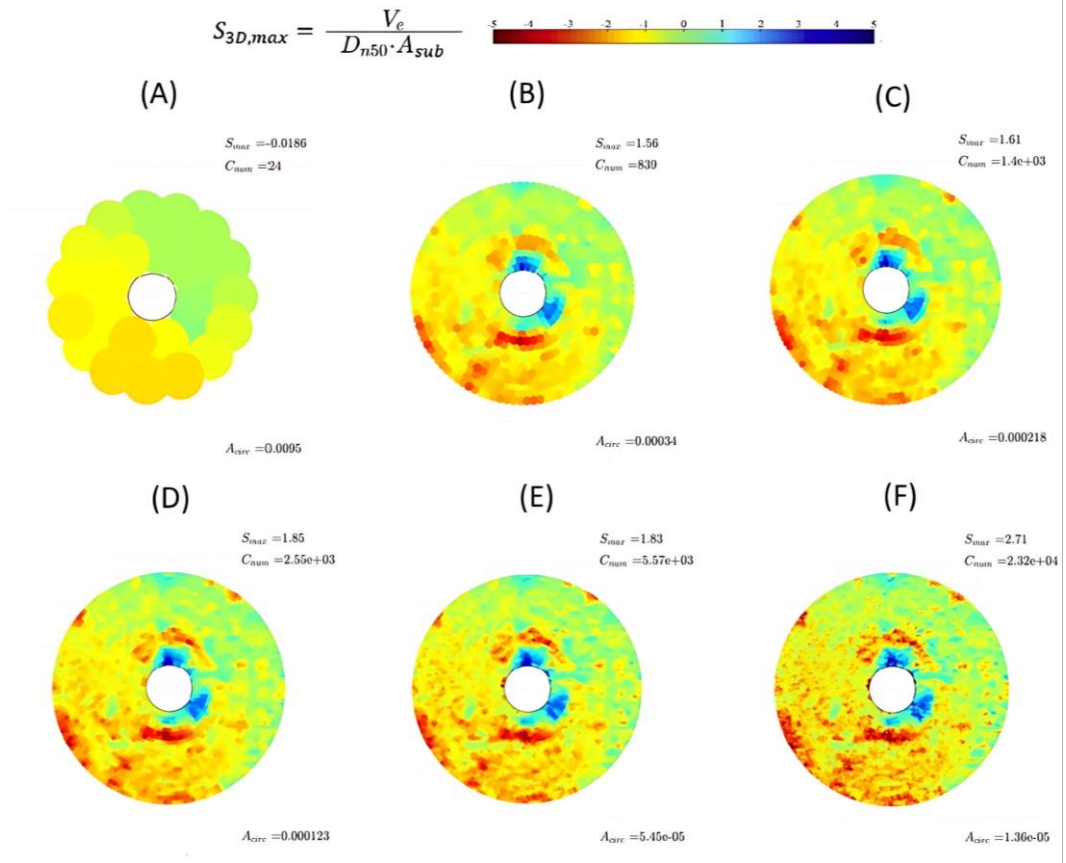


Figure 46 – Influence of $\eta_{S3D,grid}$ on $S_{3D,max}$ value for test M_WC_11: (A) $\eta_{S3D,grid}=1.43 \times 10^{-3}$, $A_{sub}=A_{pile}$; (B) $\eta_{S3D,grid}=1/25$, $A_{sub}=25D_{n50}^2$; (C) $\eta_{S3D,grid}=1/16$, $A_{sub}=16D_{n50}^2$; (D) $\eta_{S3D,grid}=1/9$, $A_{sub}=9D_{n50}^2$; (E) $\eta_{S3D,grid}=1/4$, $A_{sub}=4D_{n50}^2$; (F) $\eta_{S3D,grid}=1$, $A_{sub}=D_{n50}^2$.

The results for $S_{3D,max}$ vs $\eta_{S3D,grid}$ across all tests in the study (see Tables in Appendix III) were plotted in Figure 47 and Figure 48. Both plots show conclusions like those in Fazeres-Ferradosa *et al.* (2020), indicating a very strong dependency and positive correlation between the damage number and the grid ratio and/or the size of the selected subarea. This demonstrates that different grid ratios yield entirely different results, potentially leading to different interpretations of scour protection behaviour. This supports the need for a uniform failure criterion when evaluating scour protection performance (Fazeres-Ferradosa *et al.*, 2020).

By comparing the results and the plots, $S_{3D,max}$ increases logarithmically until approximately $\eta_{S3D,grid}=1/10$ ($A_{sub}=10D_{n50}^2$). The values appear to stabilise at that grid ratio up to $\eta_{S3D,grid}=1/4$ ($A_{sub}=4D_{n50}^2$), after which they begin to increase linearly for cases with lower scour damage (monopiles). In contrast, for cases with significant damage (hybrid monopile), $S_{3D,max}$ value remains nearly unchanged regardless of the A_{sub} chosen. Overall, the results suggest that the best range of grid ratios and sub-area sizes for accurately assessing the damage number is between $\eta_{S3D,grid}=1/6$ ($A_{sub}=6D_{n50}^2$) and $\eta_{S3D,grid}=1/4$ ($A_{sub}=4D_{n50}^2$), where minimal or no differences are observed. These findings indicate that the sub-area for failure criterion of $4D_{n50}^2$ (den Boon *et al.*, 2004) is a reasonable threshold for identifying failure in scour protection and for selecting an appropriate A_{sub} for the overlapping method.

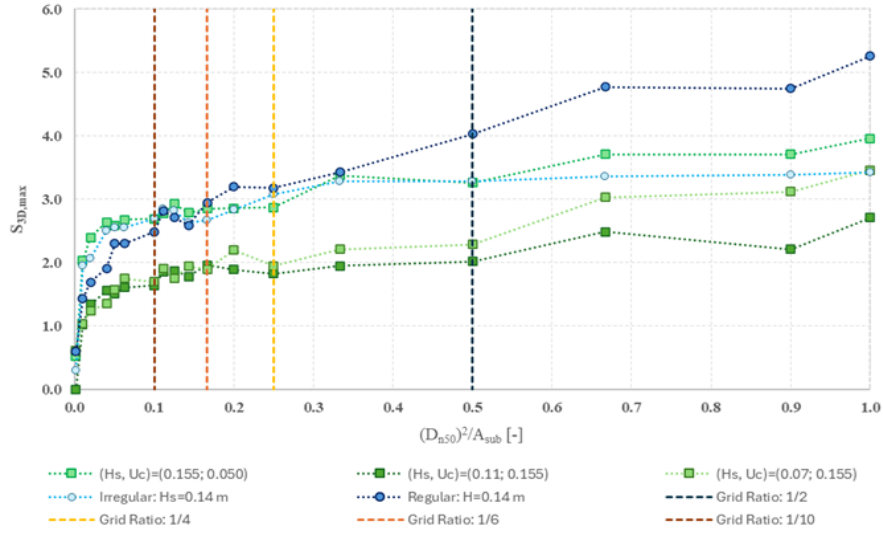


Figure 47 – Variation of $S_{3D,max}$ with $\eta_{S3D,grid}$ (monopile tests).

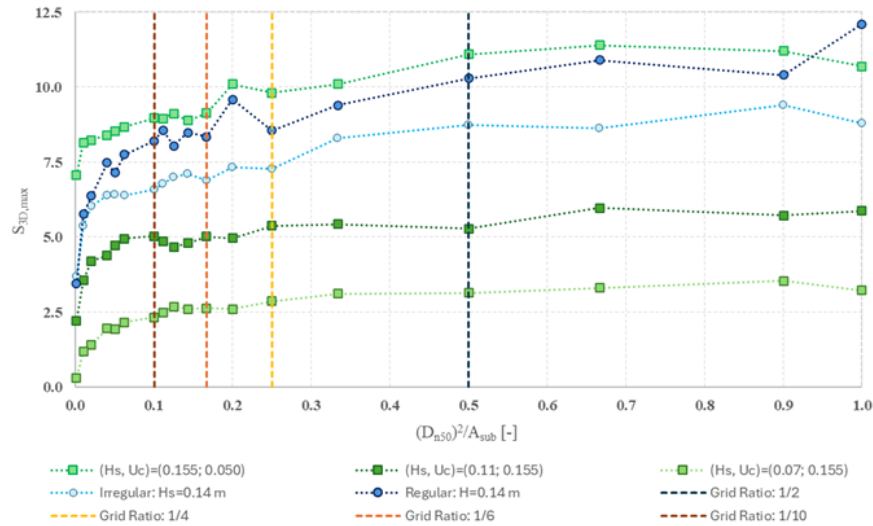


Figure 48 – Variation of $S_{3D,max}$ with $\eta_{S3D,grid}$ (hybrid monopile tests).

Since $S_{3D,max}$ appears to be significantly influenced by variations in the grid ratio and minimal changes, reinforcing the evidence reported by Fazeres-Ferradosa *et al.* (2020), the standard deviation and the 95th percentile (P_{95}) for the monopile tests were plotted in Figure 49 and Figure 50, respectively, to verify whether convergence was achieved for the different selected grid ratios. Both plots draw similar conclusions to those in the study by Fazeres-Ferradosa *et al.* (2020), showing a very strong dependency and a positive correlation between the damage number and the grid ratio and/or the size of the selected sub-area. Therefore, different grid ratios yield distinct outcomes, potentially leading to different interpretations of scour protection behaviour. This highlights the importance and necessity of applying a uniform failure criterion to assess the performance of scour protection systems.

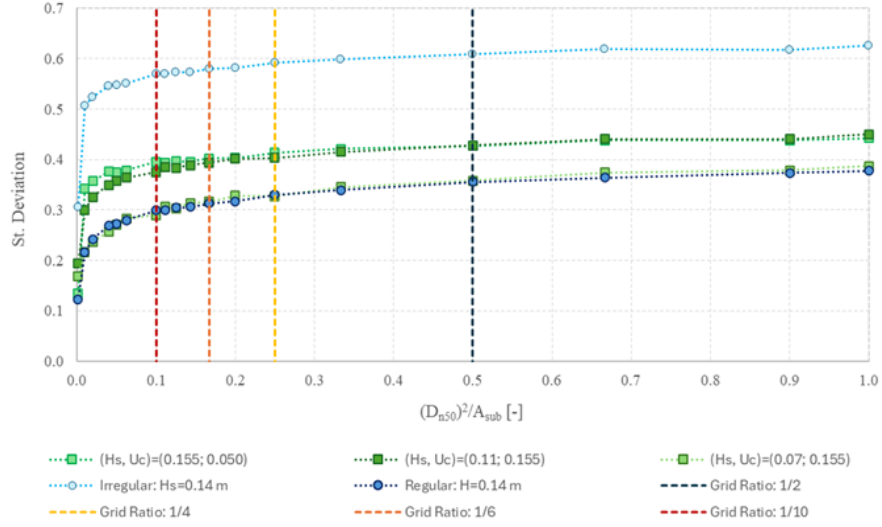


Figure 49 – Variation of the standard deviation with $\eta_{S3D,grid}$ (monopile tests).

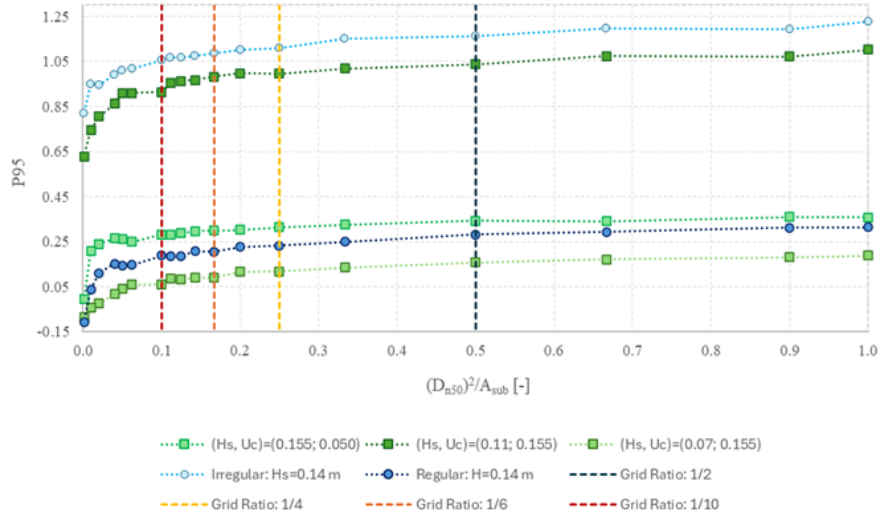


Figure 50 – Variation of the P_{95} with $\eta_{S3D,grid}$ (monopile tests).

4.4. ALTERNATIVE DAMAGE METRICS

Broekema *et al.* (2024) raised awareness on the importance of developing a scour protection design formula that combines scour depth, area, and volume, along with guidelines on the volume–area–depth relationship. Following the methodology of Fazeres-Ferradosa *et al.* (2020), it is possible to generalise a relation between the eroded volume (V_e), the area, and the scour depth (S), assuming an S_{3D} value for $A_{sub}=n_s \cdot D_{n50}^2$.

$$\frac{V_e}{A_{sub}} = S = S_{3D} \times D_{n50} \quad (19)$$

$$\frac{V_e}{S} = A_{sub} = n_s \cdot D_{n50}^2 \quad (20)$$

$$\frac{A_{sub}}{S} = (n_s \cdot D_{n50}) / S_{3D} \quad (21)$$

Furthermore, assessing the ratio S/D is a common practice in the literature when analysing scour rates for unprotected structures. Conversely, evaluating the deformation of riprap scour protections becomes unnecessary, as S/D decreases, sometimes to residual levels, and no longer aids in interpreting the condition of the protection. Considering this and the limitations of the fixed sub-areas approach De Vos *et al.* (2012), a new ratio was introduced by De Schoessiter *et al.* (2014), called the damage increase ratio ($\Delta S_{3D}/n_s$), to measure the change in damage between each wave train while accounting for the thickness of the scour protection layer, using the number of stone sizes. The experimental test results identified specific ranges of values for the damage increase ratio corresponding to different scour protection behaviours (static, dynamic, failure) over three durations (0 to 1000 waves, 1000 to 3000 waves, and 3000 to 5000 waves):

- **From 0 to 1000 waves:** $\Delta S_{3D}/n_s=[0.05-0.09]$ (static), $\Delta S_{3D}/n_s=[0.07-0.39]$ (dynamic), $\Delta S_{3D}/n_s=[0.19-0.42]$ (failure).
- **From 1000 to 3000 waves:** $\Delta S_{3D}/n_s=[0.00-0.03]$ (static), $\Delta S_{3D}/n_s=[0.00-0.12]$ (dynamic), $\Delta S_{3D}/n_s=[0.00-0.50]$ (failure).
- **From 3000 to 5000 waves:** $\Delta S_{3D}/n_s=[-0.02-0.01]$ (static), $\Delta S_{3D}/n_s=[-0.01-0.07]$ (dynamic), $\Delta S_{3D}/n_s=[-0.04-0.17]$ (failure).

By comparing the values in Table 19, most damage occurs during the first 1000 waves, but at higher rates than those proposed by De Schoessiter *et al.* (2014). However, for wave durations of 1000 to 3000, the values align with the suggested range. By strictly analysing the ratio values, it is possible to determine the speed and rate at which damage develops, but it is difficult to identify the condition and/or behaviour of the protection. Therefore, instead of using S/D and $\Delta S_{3D}/n_s$ ratio, which lack a clear physical meaning and can be ambiguous, and given that the $\Delta S_{3D}/n_s$ ratio has overlapping ranges for different behaviours, this study proposes a slight adaptation: S/D becomes S/t_s , and $\Delta S_{3D}/n_s$ becomes S_{3D}/n_s , both for a specific sub-area.

These slight modifications make both ratios more practical and intuitive and better reflect the scour-protected deformation state and the relative amount of armour-layer thickness loss. For these ratios, the

authors suggest that the limits proposed by De Vos *et al.* (2012), 0.25 for static behaviour and 1.0 for failure, could serve as a more sensible initial benchmark than for S_{3D} :

- S_{3D}/n_s or $S/t_s > 1$: failure—filter layer exposed, loss of filter layer and/or seabed lowering.
- $0.25 < S_{3D}/n_s$ or $S/t_s < 1$: dynamic behaviour, loss of thickness in the armour layer and/or movement of the armour layer units.
- $0 < S_{3D}/n_s$ or $S/t_s < 0.25$: static behaviour, no movement, or residual movement, of armour layer units.
- S_{3D}/n_s or $S/t_s < 0$: accretion of sediments around the armour layer unit.

Table 19 – Damage increase ratio ($\Delta S_{3D}/n_s$) results.

Test	Visual Classification	$\Delta S_{3D}/n_s$
M_WC_7_1000	Slightly Dynamic	0.57 (0–1000 waves)
M_WC_7_2000		0.21
M_WC_7_3000		(1000–3000 waves)
M_WC_11_1000	Dynamic	0.69 (0–1000 waves)
M_WC_11_2000		0.04
M_WC_11_3000		(1000–3000 waves)
M_WC_15.5_1000	Failure	1.15
M_WI_14_1000	Dynamic (Almost Failure)	1.11 (0–1000 waves)
M_WI_14_2000		0.12
M_WI_14_3000		(1000–3000 waves)
M_WR_14_1000	Failure	1.27 (0–1000 waves)
M_WR_14_2000		0.01
M_WR_14_3000		(1000–3000 waves)
MH_WC_7_1000	Failure	0.79 (0–1000 waves)
MH_WC_7_2000		0.36
MH_WC_7_3000		(1000–3000 waves)
MH_WC_11_1000	Failure	2.15
MH_WC_15.5_1000	Failure	3.92
MH_WI_14_1000	Failure	2.91
MH_WR_14_1000	Failure	3.42

For most tests, a variable limit for the damage number and the S/t_s ratio was used to classify and assess scour protection behaviour throughout the entire experimental campaign. The protections where failure was detected visually or by the overlapping-circle method correspond to $S_{3D} > 2.5$ or $S/t_s > 1.0$ (Table 20, Figure 47, Figure 48, and Figure 51). The same applies to protections classified as dynamic, where $S_{3D} < 2.5$ or $S/t_s < 1.0$, except for the M_WI test, for the previously mentioned reasons. Therefore, it is worth noting that a failure criterion based on S_{3D}/n_s or S/t_s is defined by the scour protection's properties and geometry and is independent of the foundation used. Higher values obtained for hybrid structures are not an indication to redefine the failure threshold, but rather an indicator of increased damage that may necessitate upgrading the scour countermeasure. Ultimately, the overlapping method proved valuable for visualising, tracking, and identifying scour patterns, holes, and rates, thereby facilitating the assessment and quantification of the damage and behaviour of each scour protection tested.

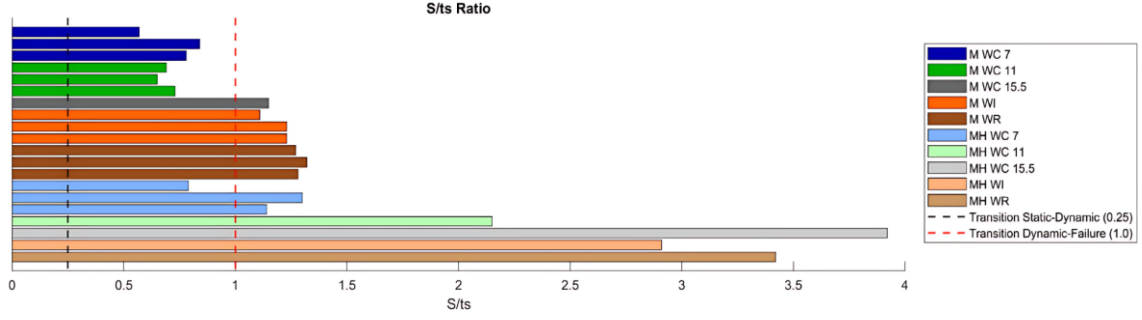


Figure 51 – S/t_s ratio values and transition thresholds – according to De Vos *et al.* (2012).

Table 20 – Scour depth (S), S_{3D}/n_s , S/t_s , and $S_{3D,measured}$ comparison with proposed failure threshold.

Test	S [mm]	S/t_s S_{3D}/n_s	S/t_s S_{3D}/n_s (Failure)	$S_{3D,measured}$	$S_{3D,failure}$
M_WC_7_1000	5.29	0.57		1.43	
M_WC_7_2000	7.80	0.84		2.11	
M_WC_7_3000	7.21	0.78		1.95	
M_WC_11_1000	6.39	0.69		1.73	
M_WC_11_2000	6.02	0.65		1.63	
M_WC_11_3000	6.76	0.73		1.83	
M_WC_15.5_1000	10.61	1.15		2.87	
M_WI_14_1000	10.24	1.11		2.77	
M_WI_14_2000	11.38	1.23		3.08	
M_WI_14_3000	11.38	1.23		3.08	
M_WR_14_1000	11.75	1.27	1.0	3.18	2.5
M_WR_14_2000	12.20	1.32		3.30	
M_WR_14_3000	11.86	1.28		3.21	
MH_WC_7_1000	7.28	0.79		1.97	
MH_WC_7_2000	12.01	1.30		3.25	
MH_WC_7_3000	10.57	1.14		2.86	
MH_WC_11_1000	19.88	2.15		5.38	
MH_WC_15.5_1000	36.26	3.92		9.81	
MH_WI_14_1000	26.91	2.91		7.28	
MH_WR_14_1000	31.60	3.42		8.55	

4.5. KC – MOB AND U_{cw} EFFECT

This section assesses the performance of scour protection using the dimensionless parameters MOB_{top} and KC_{tot} , based on a predictive model developed by Broekema *et al.* (2024). Although the proposed formula, Equation (8), effectively characterises scour deformation in conventional monopile foundations, its application to hybrid structures was not considered. The MOB_{top} – KC_{tot} framework showed a stronger correlation with scour depth and was the most reliable overall predictor of scour protection performance compared with the $stab$ parameter or S_{3D} (Broekema *et al.*, 2024). However, calculating the absolute and dimensionless predicted scour depths (S and S/D , respectively) using Equation (8) consistently underestimated the measured values for monopiles, which were 2 to 7 times higher than predictions (Table 21). Similar trends were observed in the hybrid monopile tests, where actual scour depths exceeded predictions by factors of 7 to 11.

In a preliminary analysis, these discrepancies may be attributed to the fact that the methodology proposed by Broekema *et al.* (2024) relied on van Steijn *et al.* (2023)'s algorithm to detect deformations and measure scour depths ($A_{sub}=20D_{50}^2$), which may dilute the localised scour effects compared to the

overlapping-circle method ($A_{sub}=4D_{n50}^2$). Additionally, the research developed by Broekema *et al.* (2024) used larger monopiles – $D_p=[0.15 - 0.30]$ m versus 0.11 m (model values) –, different scour protection configurations – $t_s=[1 - 2]D_{n50}$ versus $t_s=2.5D_{n50}$, protection extent of $3D_p$ versus $5D_p$, $\rho_s=[2650 - 3200]$ kg/m³ versus 2666 kg/m³, and $D_{85}/D_{15}=[1 - 3]$ versus $D_{85}/D_{15} = 3$, and different geometrical scales. Furthermore, the dataset (20 test points) in this experimental study was sparse compared to the 380 tests conducted by Broekema *et al.* (2024).

When a more detailed analysis was undertaken, a key factor identified as a possible cause of the discrepancy in the prediction values was the armour layer material's gradation width. Since Equation (22) was adopted by Broekema *et al.* (2024) to calculate the critical Shields parameter, the gradation of the armour layer material should be considered. As the model protection material was considered a very wide-graded scour protection ($D_{85}/D_{15}=3$), De Vos *et al.* (2011) recommend a lower value of θ_{cr} for calculating the $stab$ parameter, which is the same as the MOB_{top} .

When the predicted relative scour depth ($S_{predicted}/D$) values were re-evaluated using the recommended $\theta_{cr}=0.035$ (see Table 22 and Figure 52). For the monopile, although most values still fell short of accurately predicting the measured results, a significant improvement was observed. S/D values for the M_WC_11, M_WI, and M_WR tests were underpredicted by factors of less than 1.5, while the S/D value for the M_WC_15.5 test was overpredicted (Figure 53).

For the hybrid monopiles, the differences between the predicted and measured S/D decreased but remained significantly different from the measured values (Table 22, Figure 52, and Figure 54). The pronounced underprediction observed for the hybrid structure, regardless of the θ_{cr} used to determine the MOB_{top} , cannot be attributed solely to omitting the gradation width from the formula. Instead, it is reasonably linked to the presence of the WEC and its major influence on scour. Equation (8) was not designed to capture WEC-induced flow amplifications and related shear stress increases caused by the paddle's motion effects, absent from the conditions used to derive the formulation.

Since the MOB_{top} measures the hydraulic loading relative to the armour layer's resistance, its variation depends not only on the protection's stability but also on changes in flow patterns. As the KC_{tot} variable reflects the contribution of wave-orbital and steady-current velocities relative to the structure, the WEC's paddle motion, by intensifying the flow patterns acting on the foundations, is expected to exert a significant effect on both parameters, substantially increasing the bed shear stress on the scour protection well above the θ_{cr} of the armour layer material. This contribution is not represented in the formula through an amplification or safety factor, leading to a significant underestimation of the predicted scour depth.

$$\theta_{cr} = \frac{0.3}{1 + 1.2D^*} + 0.055(1 - \exp[-0.02D^*]) \quad (22)$$

Nonetheless, the discrepancy between measured and predicted scour depths for the hybrid monopile, compared to the monopile foundation, highlights the limitations of current predictive models in capturing the complexity introduced by hybrid structures, WEC components, and the integration of oscillatory movement in unsteady flow fields and offshore hydrodynamics. This emphasises the need for new predictive approaches tailored to multifunctional offshore structures that incorporate *in situ* flow and seabed-erosion measurements.

Table 21 – Measured vs. Predicted scour depth, KC_{tot} , and MOB_{top} according to Equation (8).

Test	No. of Waves	S [mm]	$S_{predicted}$ [mm]	S/D	$S_{predicted}/D$	KC_{tot}	MOB_{top}
M_WC_7_1000	1000	5.29	1.10	0.048	0.010	3.27	0.26
M_WC_7_2000	1000	7.80	1.10	0.071	0.010	3.29	0.26
M_WC_7_3000	1000	7.21	1.10	0.066	0.010	3.29	0.26
M_WC_11_1000	1000	6.39	2.31	0.058	0.021	4.19	0.36
M_WC_11_2000	1000	6.02	2.64	0.055	0.024	4.29	0.38
M_WC_11_3000	1000	6.76	3.08	0.061	0.028	4.42	0.41
M_WC_15.5_1000	1000	10.61	7.59	0.096	0.069	5.25	0.62
M_WI_14_1000	1000	10.24	3.96	0.093	0.036	4.04	0.51
M_WI_14_2000	1000	11.38	3.96	0.103	0.036	4.04	0.51
M_WI_14_3000	1000	11.38	3.96	0.103	0.036	4.04	0.51
M_WR_14_1000	1000	11.75	4.73	0.107	0.043	4.33	0.54
M_WR_14_2000	1000	12.20	4.73	0.111	0.043	4.24	0.55
M_WR_14_3000	1000	11.86	4.73	0.108	0.043	4.24	0.55
MH_WC_7_1000	1000	7.28	0.99	0.066	0.009	2.79	0.25
MH_WC_7_2000	1000	12.01	1.10	0.109	0.010	3.23	0.25
MH_WC_7_3000	1000	10.57	1.10	0.096	0.010	3.24	0.25
MH_WC_11_1000	1000	19.88	3.08	0.181	0.028	4.40	0.41
MH_WC_15.5_1000	1000	36.26	7.04	0.330	0.064	4.92	0.63
MH_WI_14_1000	1000	26.91	4.40	0.245	0.040	4.35	0.52
MH_WR_14_1000	1000	31.60	4.29	0.287	0.039	4.31	0.51

Table 22 – Comparison of scour depth predicted values using different θ_{cr} formulations.

Test	No. of Waves	S [mm]	S/D	$S_{predicted}$ [mm] $\theta_{cr}=0.035$	$S_{predicted}/D$	$S_{predicted}$ [mm] $\theta_{cr}: \text{Equation (22)}$	$S_{predicted}/D$
M_WC_7_1000	1000	5.29	0.048	1.98	0.018	1.10	0.010
M_WC_7_2000	1000	7.80	0.071	1.98	0.018	1.10	0.010
M_WC_7_3000	1000	7.21	0.066	1.98	0.018	1.10	0.010
M_WC_11_1000	1000	6.39	0.058	4.18	0.038	2.31	0.021
M_WC_11_2000	1000	6.02	0.055	4.73	0.043	2.64	0.024
M_WC_11_3000	1000	6.76	0.061	5.72	0.052	3.08	0.028
M_WC_15.5_1000	1000	10.61	0.096	14.30	0.130	7.59	0.069
M_WI_14_1000	1000	10.24	0.093	7.48	0.068	3.96	0.036
M_WI_14_2000	1000	11.38	0.103	7.48	0.068	3.96	0.036
M_WI_14_3000	1000	11.38	0.103	7.48	0.068	3.96	0.036
M_WR_14_1000	1000	11.75	0.107	9.02	0.082	4.73	0.043
M_WR_14_2000	1000	12.20	0.111	8.80	0.080	4.73	0.043
M_WR_14_3000	1000	11.86	0.108	8.80	0.080	4.73	0.043
MH_WC_7_1000	1000	7.28	0.066	1.87	0.017	0.99	0.009
MH_WC_7_2000	1000	12.01	0.109	1.98	0.018	1.10	0.010
MH_WC_7_3000	1000	10.57	0.096	1.98	0.018	1.10	0.010
MH_WC_11_1000	1000	19.88	0.181	5.72	0.052	3.08	0.028
MH_WC_15.5_1000	1000	36.26	0.330	13.09	0.119	7.04	0.064
MH_WI_14_1000	1000	26.91	0.245	8.47	0.077	4.40	0.040
MH_WR_14_1000	1000	31.60	0.287	7.92	0.072	4.29	0.039

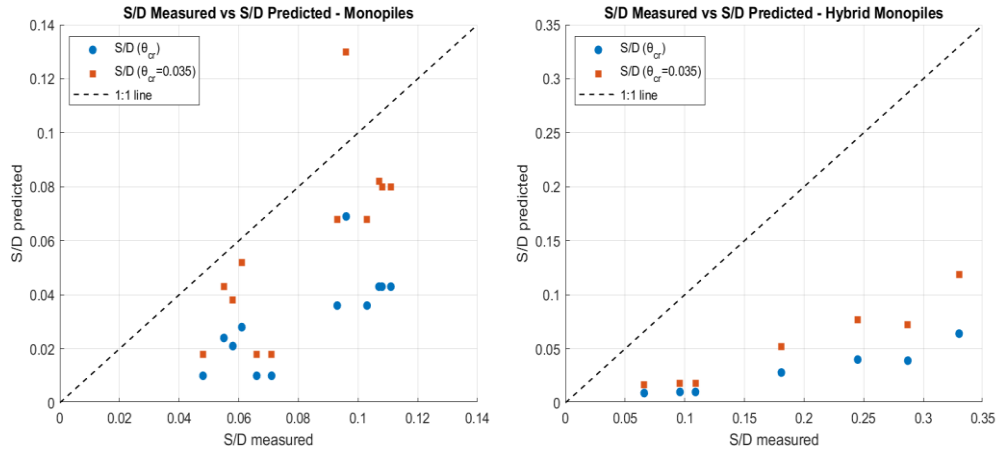


Figure 52 – Measured vs. predicted S/D , using different θ_{cr} values (Chambel *et al.*, 2025) – Equation (8).

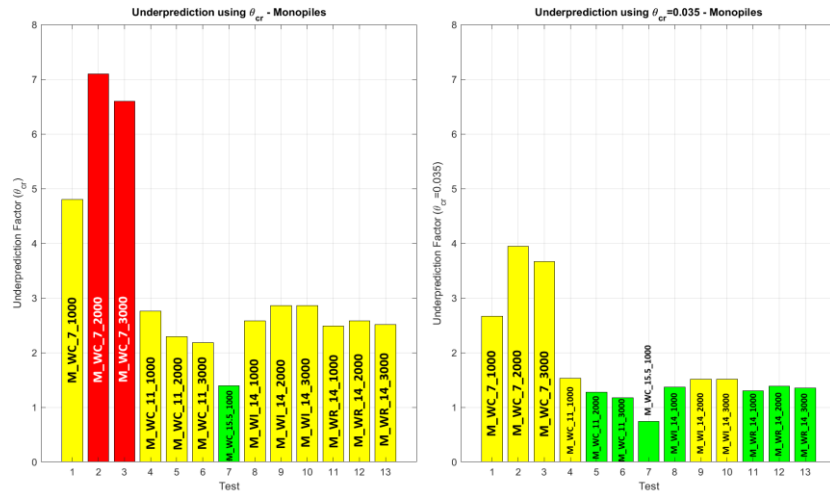


Figure 53 – Underprediction factor for monopiles, using different values for the θ_{cr} : under 1.5 times (green); between 1.5 and 5 times (yellow); over 5 times (red).

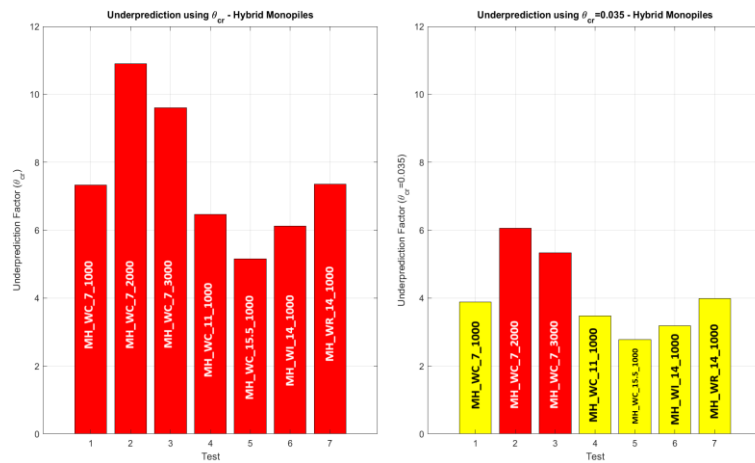


Figure 54 – Underprediction factor for hybrid monopiles, using different values for the θ_{cr} : between 1.5 and 5 times (yellow); over 5 times (red).

Among the available metrics for assessing scour protection, the parameters S/t_s and S_{3D}/n_s are more reliable indicators of damage and/or predictors than the S/D ratio. Unlike the relative scour depth, which lacks a clear physical correlation with the specific characteristics of the armour layer, such as D_{n50} or overall thickness, both S/t_s and S_{3D}/n_s directly provide quantifiable measures of the armour layer's current state. For example, a specific S/D value, even with known protection characteristics, provides limited insight into the protection's behaviour, failing to indicate whether failure has occurred or whether the scour countermeasure is in a dynamic or static state. While it can quantify erosion magnitudes, it provides only a general understanding of damage, without qualitative information on protection status or its integrity. It is more useful where scour occurs without protection, as the magnitude of seabed erosion relative to the monopile gives a general sense of risk to the foundation's ultimate or serviceability limit states. Conversely, S/t_s and S_{3D}/n_s directly and clearly indicate the percentage of eroded protection in the evaluated area, providing a straightforward, actionable view of its condition. Furthermore, for hybrid structures, where altered flow patterns caused by the paddles' movements and increased turbulence influence erosion of the rubble-mound material, these parameters also provide a credible and simpler visual interpretation of the protection's behaviour.

Although Broekema *et al.* (2024) consider the classification of scour protections into deformation classes based on the $MOB_{top} - KC_{tot}$ evaluation to be more useful than the traditional behaviour classification (static, dynamic, and failure), it also recognises that this evaluation is not always straightforward and can be difficult to determine. As shown in Figure 55 and Figure 56, most tests fall within multiple deformation classes. An attempt was made to assign a specific deformation class to each test based on the description provided by Broekema *et al.* (2024), the photographic record taken during the tests, and the DTM and S_{3D} distribution results (Table 23).

Although the monopile tests were found to fall within one of the expected classes of deformation, a distinction was made in Broekema *et al.* (2024) based on whether the deformation occurred predominantly in the upstream or downstream area of the pile. During the experimental tests in this study, damage was observed mainly in the vicinity of the pile, well within the amplification area, on both the right and left sides. Moreover, in some cases, the deformation pattern was not evident in the photographic records.

It was only perceptible using the DTMs and the S_{3D} results with the overlapping method described in Fazeres-Ferradosa *et al.* (2020). Additionally, according to the descriptions of each class provided by Broekema *et al.* (2024), the M_WC_15.5, M_WI, and M_WR tests should be classified as class 6, since that class is associated with tests conducted at low current velocities or under wave-only conditions. The tests M_WC_11 (1000 waves) and M_WC_11 (2000 waves) were classified as class 1, despite Figure 55 showing that they lie outside the class boundary. However, Broekema *et al.* (2024) also reported that many tests expected to fall within a certain class may lie within the limits of other classes, or even outside all defined class boundaries, due to significant overlaps.

Regarding the hybrid monopile tests, only the MH_WC_7 test sequence was in identifiable conditions to be placed within one of the described classes. For all remaining tests, the scour damage was too extensive to identify a potential dominant deformation location in the protection or its absence. Therefore, considering the definitions of each class presented in Broekema *et al.* (2024), each test was classified into the most appropriate class based on the hydrodynamic conditions used in each test, and a "+" sign was added in front as a note of the extensive damage observed.

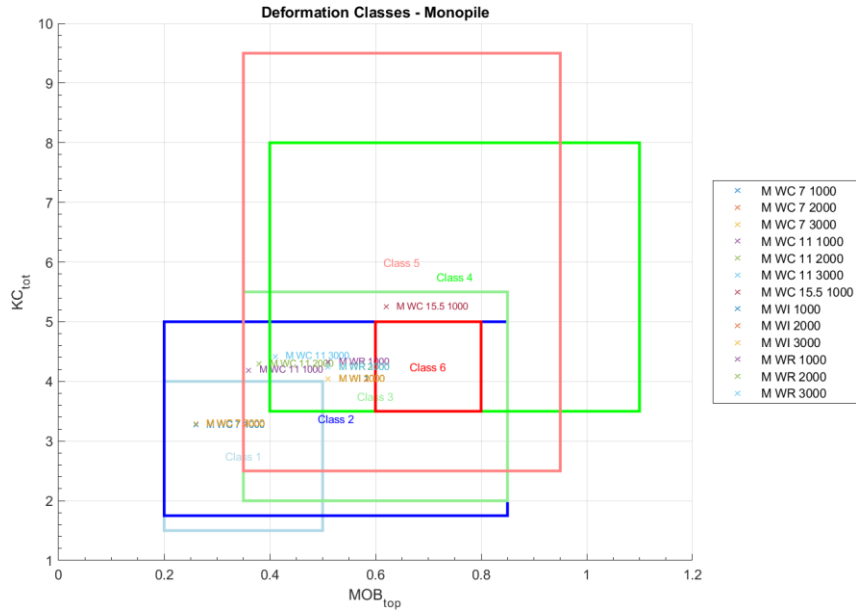


Figure 55 – Deformation classes for monopile tests.

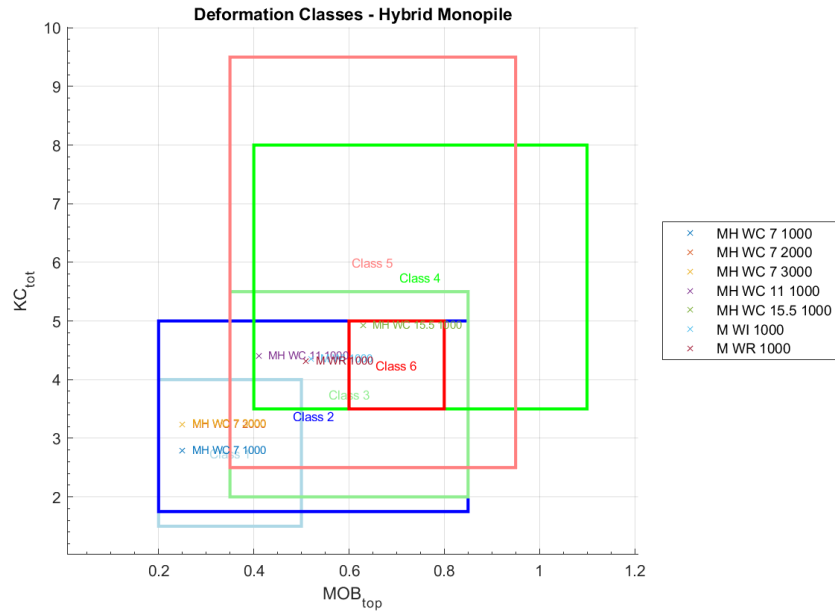


Figure 56 – Deformation classes for hybrid monopile tests.

While categorising deformations by classes is considered more useful by Broekema *et al.* (2024), it is neither a straightforward nor a simple task. Differentiating and classifying deformations from low to extreme scour can be difficult due to overlapping or even superimposed classes. Moreover, there may be deformation classes that are not constrained by any boundary condition. This renders this classification system highly subjective and less intuitive than the standard classification (static, dynamic, failure). However, directly comparing MOB_{top} and KC_{tot} to the damage number proved to be noteworthy.

Table 23 – Assessment of deformation class according to the criteria defined by Broekema *et al.* (2024).

Test	Deformation Class Assessment	Possible Classes (Figure 55 and Figure 56)
M_WC_7_1000	Class 1	
M_WC_7_2000	Class 1	Class 1 or 2
M_WC_7_3000	Class 1	
M_WC_11_1000	Class 1	Class 2, 3, or 5
M_WC_11_2000	Class 1	Class 2, 3, or 5
M_WC_11_3000	Class 3	Class 2–5
M_WC_15.5_1000	Class 2 (or 6)	Classes 3–5
M_WI_14_1000	Class 2 (or 6)	
M_WI_14_2000	Class 2 (or 6)	Classes 2–5
M_WI_14_3000	Class 2 (or 6)	
M_WR_14_1000	Class 2 (or 6)	
M_WR_14_2000	Class 2 (or 6)	Classes 2–5
M_WR_14_3000	Class 2 (or 6)	
MH_WC_7_1000	Class 1	
MH_WC_7_2000	Class 3	Class 1 or 2
MH_WC_7_3000	Class 3	
MH_WC_11_1000	Class 4+	Class 2–5
MH_WC_15.5_1000	Class 3+	Classes 2–6
MH_WI_14_1000	Class 6+	Classes 2–5
MH_WR_14_1000	Class 6+	Classes 2–5

Overall, S_{3D} tends to increase with higher values of both variables (Figure 57). Regarding the monopile tests, it shows a stronger correlation with the MOB_{top} number than with the KC_{tot} parameter (weak correlation). Since MOB_{top} measures hydraulic loading relative to the armour layer's resistance, essentially reflecting the potential for armour layer unit erosion or movement, it provides valuable information about the scour protection's resistance to loads and its likelihood of failure. Therefore, it directly captures the actual effects of the main scour mechanisms on erosion, resulting in a higher correlation with the damage number.

On the contrary, although KC_{tot} measures the wave–current contribution relative to the structure, it is closely related to shear-stress amplification and vortex shedding around the monopile, whereas the primary causes of scour are ultimately a composite of factors. As a result, it may obscure the direct contribution of each hydrodynamic component to scour under different flow conditions, since they can vary independently. Given that multiple wave–current regime combinations can produce identical KC_{tot} values, relying solely on this parameter might lead to less accurate interpretations of the primary scour driver. This may explain the observed low correlation with the damage number.

Regarding the hybrid monopile tests, since severe scour deformations were observed, a strong link between both KC_{tot} and MOB_{top} to S_{3D} was anticipated. The interaction between the WEC paddles and the flow creates a highly energetic environment near the seabed. The resulting scour deformation is affected by intensified oscillatory flow patterns, as measured by the Keulegan-Carpenter number, and by increased hydraulic stress on the seabed protection, as measured by the mobility parameter. Consequently, the high correlation with the damage number was confirmed, indicating that scour is jointly influenced by enhanced shear stresses and the armour layer's capacity, or lack of it, to withstand them. Since the relationship between S_{3D} and the $MOB_{top} - KC_{tot}$ model showed mixed results across different structures, a more detailed analysis was undertaken.

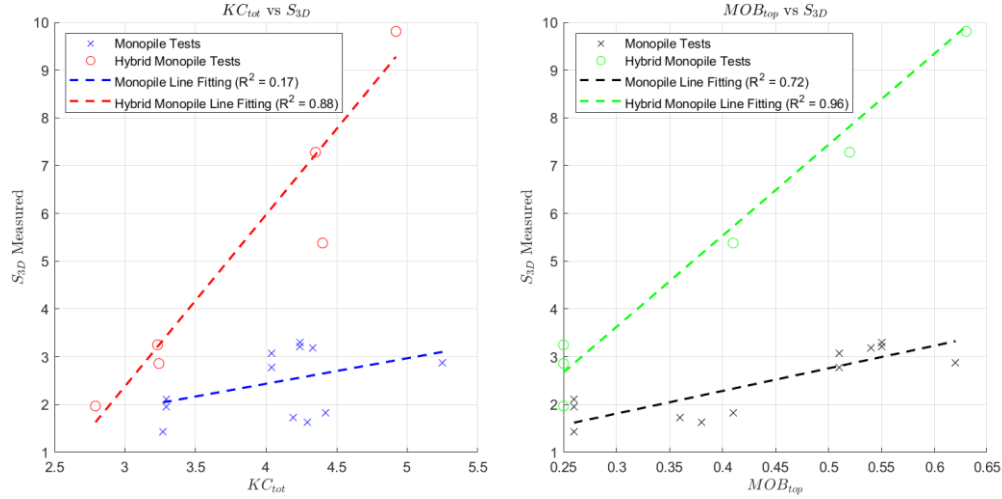


Figure 57 – Damage number comparison with KC_{tot} number (left) and MOB_{top} parameter (right).

This analysis considers the influence of KC_{tot} (wave–current contribution), KC (wave contribution), and KC_c (current contribution). An evaluation of the U_{cw} ratio relative to the S_{3D} was also performed, as previous studies have reported a general trend of increased scour depths with higher U_{cw} values across various conditions (Chen and Li, 2018; Schendel *et al.*, 2020; Sumer and Fredsøe, 2001; Rudolph and Bos, 2006; Sumer *et al.*, 2013; Qi and Gao, 2014). The literature indicates that, for the same U_{cw} value, scour depths tend to be greater at higher KC values (Schendel *et al.*, 2020). This pattern was notably more evident in wave-dominant regimes. As U_{cw} increases, the correlation weakens, and for $U_{cw} > 0.65$, scour depths remain nearly constant and independent of KC .

As previously mentioned, although the KC_{tot} is directly linked to increases in shear stress and scour, a clearer understanding of the main scour drivers for each foundation emerges when its wave and current components are examined separately (Table 24). For the hybrid monopile, the results show strong positive correlations between the KC_{tot} and KC , emphasising the dominant role of wave-induced velocities amplified by the WEC in scour development (Figure 58). The moderate inverse correlation with KC_c (Figure 59) suggests a comparatively minor influence of currents on scour for this type of structure. For the monopiles, a strong positive correlation with KC and a strong negative correlation with KC_c were observed (Figure 58 and Figure 59). This supports the earlier suggestion that the combined parameter may obscure the distinct effects of each hydrodynamic component on scour, since for the same KC_{tot} value, multiple KC and KC_c combinations are possible. Ultimately, the strong correlation between damage and KC and KC_c , despite a weaker correlation with KC_{tot} , indicates that monopile scour depends heavily on the complex interaction between these two main hydrodynamic loads, which may not be fully captured by a single combined parameter.

When evaluating the specific influence of the four parameters (KC_{tot} , KC , KC_c , and U_{cw}) on the damage number, each assessment should be done carefully. The apparent inverse relationship between U_{cw} and S_{3D} (Figure 59) reflects the hydrodynamic conditions chosen for the tests, in which higher S_{3D} values occurred at lower U_{cw} ratios and at higher wave heights with lower current velocities (high KC and low KC_c). Conversely, lower scour damage rates were observed in tests with higher U_{cw} ratios, which corresponded to lower wave heights and higher current velocities (low KC and high KC_c). However, when analysing tests with similar KC_{tot} values, for example, M_WC_11 ($U_{cw}=0.55$, $KC_{tot} \approx 4.2$ to 4.4 , $KC \approx 1.9$ to 2.1) versus M_WR_14 ($U_{cw}=0$, $KC_{tot}=KC \approx 4.2$ to 4.3), the test with the higher KC

(M_WR_14) showed an almost 60 to 90% increase in the S_{3D} value. Furthermore, comparing the wave-only tests (M_WI versus M_WR) with the same U_{cw} , the series with the higher KC value exhibited slightly greater scour damage, as noted by Schendel *et al.* (2020). Regarding tests with higher U_{cw} ratios, those with smaller KC numbers showed similar S_{3D} values in monopile tests, slightly higher for the $H_s=0.07$ m (model) and $U_{cw}=0.65$ combination than for $H_s=0.11$ m (model) and $U_{cw}=0.55$, consistent with observations by Chen and Li (2018); Schendel *et al.* (2020); Sumer and Fredsøe (2001); Rudolph and Bos (2006); Sumer *et al.* (2013); Qi and Gao (2014).

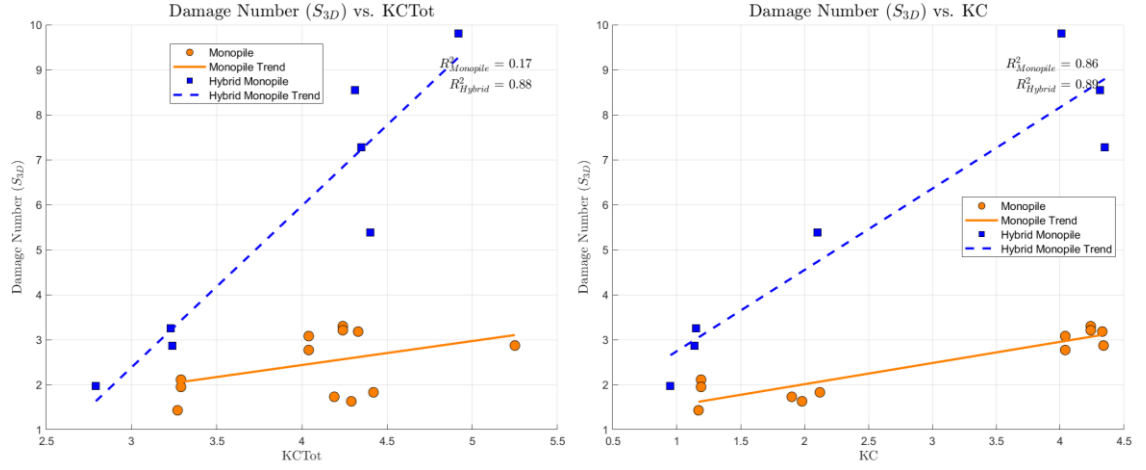


Figure 58 – S_{3D} vs. KC_{tot} and KC number (monopile and hybrid monopile tests).

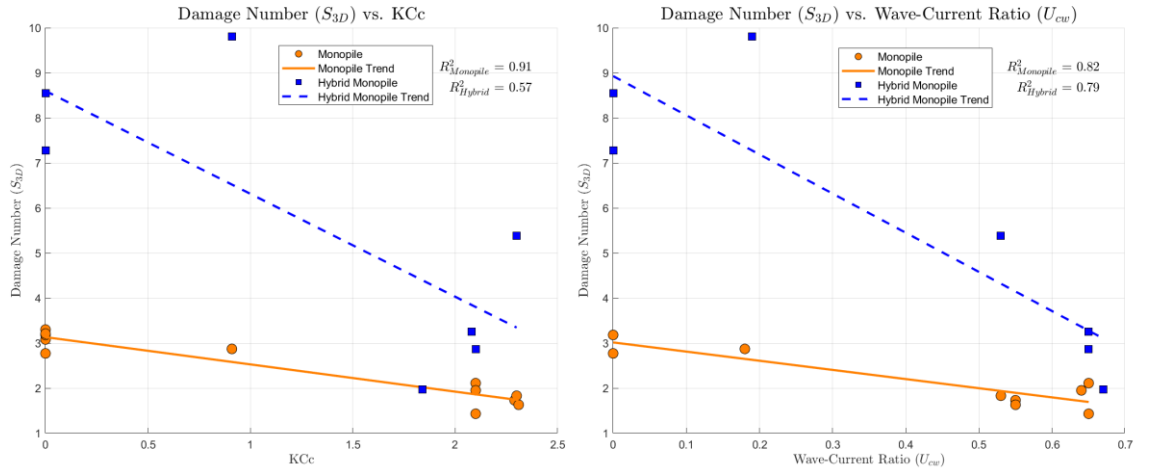


Figure 59 – S_{3D} vs. KCc and U_{cw} ratio (monopile and hybrid monopile tests).

Overall, the results indicate that scour damage rises with increasing KC values, regardless of the prevailing regime. Comparing the monopile test results with those of the hybrid monopile, the effect previously seen for lower U_{cw} ratios was more significant in the hybrid monopile tests. This difference can be attributed to the unique hydrodynamic interactions arising from the oscillating paddle motion of the OSWEC. In wave-dominated regimes, this oscillatory motion leads to significant variations in local flow velocities and conditions. These interactions increase bed shear stress, turbulence, and flow

acceleration around the structure, serving as an additional source of scour-inducing force and thereby encouraging greater sediment transport than conventional monopile foundations under similar conditions.

Table 24 – $S_{3D,measured}$, U_{cw} , KC , KC_c , and KC_{tot} comparison.

Test	U_{cw}	KC	KC_c	KC_{tot}	$S_{3D,measured}$
M_WC_7_1000	0.65	1.17	2.10	3.27	1.43
M_WC_7_2000	0.65	1.19	2.10	3.29	2.11
M_WC_7_3000	0.64	1.19	2.10	3.29	1.95
M_WC_11_1000	0.55	1.90	2.29	4.19	1.73
M_WC_11_2000	0.55	1.98	2.31	4.29	1.63
M_WC_11_3000	0.53	2.12	2.30	4.42	1.83
M_WC_15.5_1000	0.18	4.34	0.91	5.25	2.87
M_WI_14_1000		4.04	0.00	4.04	2.77
M_WI_14_2000	0.00	4.04	0.00	4.04	3.08
M_WI_14_3000		4.04	0.00	4.04	3.08
M_WR_14_1000		4.33	0.00	4.33	3.18
M_WR_14_2000	0.00	4.24	0.00	4.24	3.30
M_WR_14_3000		4.24	0.00	4.24	3.21
MH_WC_7_1000	0.67	0.95	1.84	2.79	1.97
MH_WC_7_2000	0.65	1.15	2.08	3.23	3.25
MH_WC_7_3000	0.65	1.14	2.10	3.24	2.86
MH_WC_11_1000	0.53	2.10	2.30	4.40	5.38
MH_WC_15.5_1000	0.19	4.01	0.91	4.92	9.81
MH_WI_14_1000	0.00	4.35	0.00	4.35	7.28
MH_WR_14_1000	0.00	4.31	0.00	4.31	8.55

4.6. WAVE TRANSMISSION AND WAVE REDUCTION COEFFICIENTS

The main goal of the experimental campaign was to assess damage to the scour protection of two structures types. However, converting a standard monopile into a hybrid structure by incorporating a WEC revealed significant flow patterns and hydrodynamic differences. Since the focus was not on the WEC's performance, the captured energy efficiency or the power-per-unit front was not calculated. Instead, straightforward metrics such as the wave transmission coefficient (K_T), which compares the seaside wave height to the leeside wave height in each test, and the wave reduction coefficient (K_{Red}), which compares the wave heights between a monopile test and a hybrid monopile test under the same hydrodynamic conditions, highlight how both structures, including the device, influence wave attenuation.

For monopile-only tests, the K_T consistently remains near 100% (Table 10), indicating minimal interference with the incoming wave. The structure's narrow cross-section contributes to this behaviour, allowing waves to propagate with negligible attenuation, which confirms the limited wave sheltering capacity—deviations in the coefficient do not exceed $\pm 5\%$. In contrast, for hybrid monopiles, the integrated WEC allows a significant reduction in the K_T , especially at higher wave heights, where almost 25% wave attenuation on the leeside was observed. These results were obtained using a simplified mechanical actuator for the WEC paddles, suggesting that a fully operational PTO system could achieve even greater attenuation. The findings support the premise that hybridisation effectively enhances dissipative capacity, improving wave absorption and reducing transmitted wave energy. Conversely, a negative aspect is that it increases flow contraction and wave-current velocities (not quantified in this study) between the bottom of the WEC and the scour protection.

Table 25 – Wave transmission coefficient (K_T) for monopile and hybrid monopile tests.

Test	No. of Waves	K_T (%)
M_WC_7_1000	1000	100.0
M_WC_7_2000	1000	100.0
M_WC_7_3000	1000	100.0
M_WC_11_1000	1000	105.0
M_WC_11_2000	1000	104.8
M_WC_11_3000	1000	102.7
M_WC_15.5_1000	1000	98.7
M_WI_14_1000	1000	99.3
M_WI_14_2000	1000	97.8
M_WI_14_3000	1000	96.3
M_WR_14_1000	1000	101.4
M_WR_14_2000	1000	102.1
M_WR_14_3000	1000	100.0
MH_WC_7_1000	1000	94.6
MH_WC_7_2000	1000	94.4
MH_WC_7_3000	1000	94.3
MH_WC_11_1000	1000	81.8
MH_WC_15.5_1000	1000	76.8
MH_WI_14_1000	1000	75.4
MH_WR_14_1000	1000	86.1

While some offshore K_{Red} values (Table 26) for the hybrid monopile show slight negative values, *i.e.*, wave enhancement up to 9%, this was attributed to the intense scour that eroded the protection and caused the seabed to be lowered, which increased the water depth, creating conditions for larger waves to be registered without breaking. The onshore K_{Red} values (Table 26) consistently indicate a substantial reduction in wave height across all hybrid tests, by up to nearly 30%. These results highlight the potential of WECs as promising components for integration into offshore structures. They may serve not only as a booster for renewable energy and power generation but also as a protective element that shields offshore structures and mitigates severe coastal erosion (Fazeres-Ferradosa *et al.*, 2021; Chambel *et al.*, 2024). Nevertheless, optimisation and strategic integration of PTO systems appear critical for addressing the scour enhancement associated with such devices. This phenomenon could otherwise undermine the overall efficiency of the hybrid structure.

Despite the presence of the WEC, a reduction in transmitted wave height was observed compared to the incident wave. However, the scour damage to the protection increased simultaneously. This indicates that the rotational angle of the converter's paddle and its distance from the seabed should be considered key design criteria to prevent excessive scour or damage to the protection. When using an OSWEC as a protective measure for a pipeline, it was concluded by Taheri *et al.* (2022) that scour was reduced by increasing the angle between the flap and the seabed, which corresponded to a reduction in the flap's rotation relative to its vertical axis, thereby minimising its oscillatory movement and velocity.

Regarding the distance of a converter from the seabed, the effect of tip clearance (defined as the vertical distance between a rotating blade and a stationary point) for tidal-current energy turbines was examined by Chen *et al.* (2017) and Sun *et al.* (2018), with the first specifically investigating turbines attached to a monopile. Both studies demonstrated that scour was amplified by the converter due to increased local velocities, downflow, and the formation of horseshoe vortices. A 10–20% increase in scour extent and a 30% increase in scour depth were reported by Sun *et al.* (2018). Furthermore, it was observed that scour increased more rapidly with smaller distances to the bed profile. Nonetheless, it was also concluded that equilibrium scour is independent of tip clearance—continuous reductions in the distance

to the sediment bed, beyond a certain point, did not lead to a significant increase in scour depth (Sun *et al.*, 2018).

Table 26 – Wave reduction coefficient (K_{Red}) for monopile and hybrid monopile tests.

Test	No. of Waves	Offshore K_{Red} (%)	Onshore K_{Red} (%)
M_WC_7 vs MH_WC_7	1000	-2.7	2.9
		2.8	9.0
		4.3	10.6
M_WC_11 vs MH_WC_11	1000	-9.1	16.7
M_WC_15.5 vs MH_WC_15.5	1000	-0.6	27.5
M_WI_14 vs MH_WC_14	1000	-1.4	29.8
M_WC_14 vs MH_WI_14	1000	3.6	22.0

While this study maintained a fixed tip clearance in line with operational recommendations for the WEC, it is important to emphasise that this parameter significantly influences scour development and could be vital to the future of hybrid structures. Future studies should explore a range of tip clearance distances and their interaction with other variables related to the WEC and foundation geometry to assess their impact under various hydrodynamic conditions. This would enable a more comprehensive understanding of its effect on scour and ultimately aid in developing tailored design criteria for scour protection of hybrid structures incorporating WEC devices.

4.7. CONCLUSIONS

Experimental results showed that although the converter, coupled into the hybrid structure model, reduced incident hydrodynamic conditions and lowered leeward wave heights by nearly 30%, the oscillatory motion of the convergent paddles generated complex flow patterns that increased the damage rate. These include downflow, horseshoe vortices, and lee-wake vortices, which intensified scour mechanisms and caused severe erosion of the armour layer unit, along with seabed lowering near the structure.

Using the overlapping-circle methodology developed by Fazeres-Ferradosa *et al.* (2020) to determine the damage number proved effective and accurate for measuring damage rates and detailing their distribution. The analysis of how the grid ratio influences the damage distribution, along with the maximum representative value, indicated a strong dependence on the size of the selected sub-area, emphasising the need for a uniform failure criterion. Results imply that a grid ratio between 1/6 and 1/4, corresponding to sub-areas of $6D_{n50}^2$ and $4D_{n50}^2$, may be appropriate for assessing the damage number, partially validating the failure criterion proposed by den Boon *et al.* (2004) as a reasonable limit. Nonetheless, the observed damage values raise significant questions regarding the applicability and conservativeness of existing design criteria and formulation (De Vos *et al.*, 2012).

The comparison between the monopile and hybrid monopile tests revealed distinct differences in scour rate and damage number. Riprap protections on hybrid structures experienced significantly more damage, leading to notable deformations and, in many cases, premature failure, often within the first 1000 waves, unlike monopiles, which, under mild conditions, maintained their integrity or showed dynamic behaviour. Although some protection configurations demonstrated some capacity for reshaping and recovery, even after considerable damage, in the case of the hybrid monopile, the flow patterns induced by the WEC caused irreversible damage to the armour layer. These findings indicate that

existing design criteria, especially those developed for monopiles (De Vos *et al.*, 2012), are inadequate for more complex and hybrid configurations. It can be argued that evaluating the S/t_s or S_{3D}/n_s ratio provides a more reliable and representative damage indicator for riprap scour protections than the S/D ratio or the $S_{3D} > 1.0$ failure limit suggested by De Vos *et al.* (2012). The proposed limits for S/t_s or S_{3D}/n_s better match the experimentally observed behaviour of the scour protections.

The scour prediction formula developed by Broekema *et al.* (2024), which relies on the MOB_{top} and KC_{tot} parameters, consistently underestimated the observed scour deformation during the tests, especially in hybrid structure cases. This discrepancy may be linked to this study's limited dataset, differences in model scales, or variations across subareas within each measurement methodology. Therefore, the methodology proposed by Broekema *et al.* (2024) also proved unsuitable for capturing the increased complexity introduced by a WEC in a hybrid structure system. Nonetheless, a strong correlation was observed between S_{3D} and KC_{tot} , as scour damage naturally correlates more closely with shear-stress amplification and vortex shedding around the monopile. Furthermore, although Broekema *et al.* (2024) reported no clear dependence on certain parameters, such as gradation width, thickness, and extent, future studies could benefit from examining the contribution of these factors, as they may exert a measurable influence on scour under combined wave-current and WEC-induced loading. Ideally, integrating the S_{3D} with the $MOB_{top} - KC_{tot}$ model could prove extremely valuable for developing a more robust approach to damage prediction for both monopiles and hybrid structures.

In summary, the novel contributions and main takeaways are hereby highlighted:

- **Application of scour protections in a hybrid monopile-WEC system:** comparative assessment of scour damage with a monopile foundation.
 - **Paddle-based WECs can intensify scour in hybrid structures:** although the used OSWEC device attenuated incoming wave heights by almost 30%, the characteristics and layout of the device can significantly alter the scour pattern due to flow contractions, downflow, and other flow pattern phenomena. Changes in pore pressure and hydraulic gradient induced by the converter require further specific analysis and modelling.
- **Application and evaluation of the innovative overlapping-circle 3D method:** demonstration of its effectiveness and high-resolution scour quantification capabilities of the method proposed by Fazerres-Ferradosa *et al.* (2020), while comparing it with two other different methods (De Vos *et al.*, 2012; Broekema *et al.*, 2024), making a sensitivity analysis to understand the need for a methodological standardisation.
 - **Overlapping method revealed limitations in existing design damage analysis methods:** the overlapping method effectively quantified scour damage via S_{3D} number, providing more insights into its behaviour, completing the information acquired from the studies performed by De Vos *et al.* (2012) and Broekema *et al.* (2024), mainly for hybrid configurations. However, its high sensitivity to the grid ratio indicates that the optimal value lies within the $1/4 - 1/6$ interval, which aligns with the proposal by Fazerres-Ferradosa *et al.* (2020).
- **Identification of limitations in existing design standards and predictive formulas:** the results lead to questioning the conservatism of existing design standards and their inability to capture WEC-induced enhanced flow complexities.
 - **Hybrid monopile riprap protections exhibited early failure:** when compared to standard monopile tests, the scour countermeasures applied to hybrid structures showed

markedly higher damage rates, often failing within the initial 1000 waves, thus indicating that the current design methods do not accommodate the dynamic loads induced by WECs.

- **Proposal of alternative performance-aligned scour metrics:** S/t_s and/or S_{3D}/n_s ratios offer more accurate and straightforward indicators for quantifying and evaluating riprap scour protection performance in complex offshore environments by shifting the comparative/relative referential from the foundation to the protection itself.
 - **Alternative S/t_s and S_{3D}/n_s indicators shown to be reliable:** these two relative scour damage ratios better represent the actual riprap state and performance under hydrodynamic loading than the traditional S/D or $S_{3D}>1.0$ threshold, offering a more reliable basis for future design approaches.
- **Framework for advancing design methodologies in hybrid offshore structure:** to update predictive tools that account for dynamic structural effects and vortex-induced shear amplifications of coupling (extra) devices, to promote safer, more adaptable infrastructures for marine harvesting technologies.

Future research should expand the experimental test matrix to include a wider range of hydrodynamic scenarios, alternative scour protection configurations, and different WEC devices. It should also investigate secondary erosion behind riprap protections, as this may become significant over long-term operational conditions. While the current study examined scour protection performance under a maximum of 3000 waves aligned with most tests reported in the literature and consistent with the duration used to develop the present design criteria, it serves as a step towards understanding the short- to mid-term behaviour of such protective systems.

Future studies should extend this research through longer physical and numerical modelling campaigns (e.g., over 5000 waves) and field observations to evaluate potential long-term damage mechanisms, including secondary erosion. Additionally, the recoverability capacity observed during the tests, which indicates dynamic stability, should also be assessed over longer durations to determine whether backfilling signifies sustainable resilience or merely delays failure temporarily. Conducting comparative tests with different types of filter layers would be valuable to see if this phenomenon persists across various configurations or signals of progressive failure. These efforts would help verify whether current design standards adequately address these long-term effects.

The use of a simplified spring-based mechanism instead of a PTO in this research enabled a controlled assessment of the primary effect of WEC paddle motion on scour. To better understand the direct impact of the converter, future experiments should include a fully operational PTO system to account for damping effects, which are expected to significantly influence flap dynamics, change flow patterns, and ultimately affect scour damage around the foundation. Additionally, the local flow enhancement caused by the hybrid structure should be directly measured using a CFD model. Such a model would allow for the evaluation of the converter's paddle motion influence on pressure field variations, quantify the increase in bed shear stress on the armour layer, and identify the relative contribution of each flow pattern to the scour damage observed on the scour protection.

Addressing these knowledge gaps will expand existing datasets and enhance understanding of the key physical mechanisms driving scour in WECs and hybrid systems. This is essential for advancing understanding of scour damage processes and, ultimately, for developing a robust predictive framework. Such efforts are vital to developing new design methodologies and formulations that accurately capture the complex interactions in these intricate marine and offshore environments.

5. Experimental Study of Scour Protections for Hybrid Jackets

5.1. INTRODUCTION

The experimental study described in Chapter 3 was also used to assess damage to a jacket and a hybrid jacket protected with a non-standard geometry scour protection. The primary objective of this chapter is to evaluate the performance of a scour protection designed according to recommendations from the literature by analysing and comparing the damage results against design criteria originally developed for monopiles. The work also advances the state of the art by presenting one of the first physical model tests of protected hybrid jackets. By coupling an OSWEC to the structure, this work quantifies how the device's oscillatory motion influences turbulence and hydrodynamics, thereby modifying the mechanisms of scour protection failure. Additionally, a novel adaptation of the overlapping-circle method is successfully applied, ensuring accurate characterisation of damage for complex foundations. The main findings were published in Chambel *et al.* (2026a) and are presented in this chapter.

5.2. DAMAGE NUMBER

To measure the damage number in a 4-legged (hybrid) jacket protected with a squared scour protection, a novel overlapping technique was developed (sub-chapter 5.3 and chapter 6). As in the analysis performed for the previous chapter, a $A_{sub}=4D_{n50}^2$ and an overlap distance of 50% were used as reference, for the quantification of damage using the overlapping method under each test condition (Table 27). The U_{cw} values distinguish wave-dominated tests ($U_{cw}<0.44$) from current-dominated tests ($U_{cw}>0.44$). The novel showed high-resolution portrayals of the scour patterns, demonstrating high accuracy in measuring S_{3D} values and depicting the spatial distribution of damage (see Appendix IV).

As expected, S_{3D} generally correlates strongly with the magnitude of the hydrodynamic load. Under low-energy conditions, the S_{3D} values were lower and increased with increasing wave height and period. Additionally, when comparing the results of the wave-only tests (J_WI vs. J_WR and JH_WI vs. JH_WR), the S_{3D} values were marginally higher with regular waves, consistent with a study by Sumer and Fredsøe (2000), regarding a rubble-mound structure, which attributed these differences to the fact that the H_{rms} for irregular waves tends to be smaller than for regular waves.

Under all tested hydrodynamic conditions, the scour protection associated with the jacket test configurations (J_WC, J_WI, and J_WR) consistently showed lower damage rates than those in hybrid jackets (JH_WC, JH_WI, and JH_WR). In line with the results from Chapter 4, the hybrid configuration exhibited noticeable scour deformations, particularly under moderate to high hydrodynamic regimes. The increase in damage was both quantitatively measured and visually confirmed, linking high S_{3D}

values to severe sediment displacement, extensive washout of the armour layer material, and substantial sinking of the seabed beneath the filter layer (Figure 60).

The damage number in the hybrid jackets increased by factors ranging from 1.71 to 6.23 (Table 28), indicating that the hydrodynamic interaction caused by the WEC has a substantially more destabilising effect on the integrity of the scour protection than the jacket's geometric complexity alone. In most hybrid jacket tests, failure occurred within the first 1000 waves, with a damage number well above the $S_{3D, failure} > 1.0$ limit set by De Vos *et al.* (2012). The only hybrid test in which the scour protection withstood the entire 3000 waves was the JH_WC_7 test. An initial visual inspection suggested a static behaviour (see Figures in Appendix IV), as no vigorous movement of the armour layer units was observed. However, the measured damage number (Table 27) was significantly above the $S_{3D, static} > 0.25$ threshold defined by De Vos *et al.* (2012), due to edge scour on the leeward side of the protection. Thus, it was visually classified as borderline between static and dynamic behaviour.

Table 27 – Experimental measured conditions for jacket and hybrid jacket tests (model values).

Test	No. of Waves	H_{m0} [m]	T_p [s]	U_m [m/s]	U_c [m/s]	U_{cw}	S_{3D} (Predicted)	S_{3D} (Measured)	KC	Visual Classification
J_WC_7_1000	1000	0.069	1.471	0.081	0.156	0.66	0.07	1.61	4.79	Static (3000 waves)
J_WC_7_2000	1000	0.068	1.471	0.080	0.157	0.66	0.08	1.76	4.72	
J_WC_7_3000	1000	0.069	1.471	0.081	0.157	0.66	0.09	1.72	4.79	
J_WC_11_1000	1000	0.100	1.695	0.130	0.158	0.55	0.36	1.67	8.83	Static (3000 waves)
J_WC_11_2000	1000	0.103	1.613	0.130	0.156	0.55	0.39	1.80	8.39	
J_WC_11_3000	1000	0.106	1.667	0.137	0.157	0.53	0.53	1.98	9.11	
J_WC_15.5_1000	1000	0.145	1.887	0.200	0.051	0.20	1.62	3.27	15.09	Dynamic (Almost Failure for the last 1000 waves)
J_WC_15.5_2000	1000	0.148	1.887	0.204	0.048	0.19	2.04	4.62	15.41	
J_WC_15.5_3000	1000	0.148	1.887	0.204	0.048	0.19	2.25	4.71	15.41	
J_WI_14_1000	1000	0.136	2.128	0.192	-	0.00	1.83	3.85	16.32	Dynamic (3000 waves)
J_WI_14_2000	1000	0.135	2.174	0.190			2.19	3.67	16.48	
J_WI_14_3000	1000	0.137	2.083	0.196			2.43	3.96	16.30	
J_WR_14_1000	1000	0.138	2.222	0.203	-	0.00	2.35	2.83	18.07	Dynamic (Almost Failure for the last 1000 waves)
J_WR_14_2000	1000	0.138	2.222	0.203			2.78	3.72	18.07	
J_WR_14_3000	1000	0.134	2.222	0.197			2.81	4.90	17.54	
JH_WC_7_1000	1000	0.068	1.471	0.080	0.155	0.66	0.06	3.02	4.72	Slightly Dynamic (3000 waves)
JH_WC_7_2000	1000	0.069	1.471	0.081	0.154	0.65	0.09	3.01	4.79	
JH_WC_7_3000	1000	0.071	1.471	0.084	0.155	0.65	0.10	3.65	4.93	
JH_WC_11_1000	1000	0.111	1.695	0.145	0.156	0.52	0.50	10.40	9.80	Failure
JH_WC_15.5_1000	1000	0.154	1.961	0.216	0.049	0.18	2.21	19.10	16.95	Failure
JH_WI_14_1000	1000	0.142	2.273	0.211	-	0.00	2.77	16.00	19.17	Failure
JH_WR_14_1000	1000	0.147	2.273	0.218	-	0.00	3.05	16.80	19.85	Failure

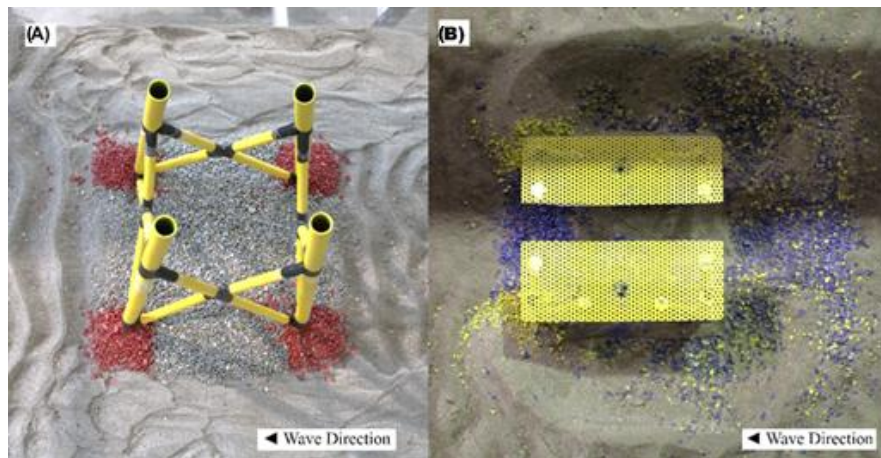


Figure 60 – Scour damage comparison after 1000 waves: (A) J_WR_14_1000 (Jacket) and (B) JH_WR_14 (Hybrid Jacket).

Table 28 – Damage amplification between jacket ($S_{3D,jacket}$) and hybrid jacket ($S_{3D,hybrid}$) tests.

Test	No. of waves	$S_{3D,hybrid}/S_{3D,jacket}$
J_WC_7 vs. JH_WC_7	1000	1.88
	2000	1.71
	3000	2.12
J_WC_11 vs. JH_WC_11	1000	6.23
	2000	-
	3000	-
J_WC_15.5 vs. JH_WC_15.5	1000	5.84
	2000	-
	3000	-
J_WI_14 vs. JH_WI_14	1000	4.16
	2000	-
	3000	-
J_WR_14 vs. JH_WR_14	1000	5.94
	2000	-
	3000	-

Although sediment-flow-structure interactions in jackets are well documented in the literature, the results from the hybrid jackets confirm that the OSWEC body and its oscillatory paddles enhance flow patterns that influence scour dynamics. The oscillatory motion of the front paddles appears to increase downflow and horseshoe vortices. In contrast, the movement of the downstream paddle appears to strengthen the intensity of the lee-wake and counter-rotating vortices. Furthermore, due to the WEC's dimensions and a higher blockage ratio, the approaching flow conditions lead to increased streamline contractions around and beneath the device.

Regarding the jacket foundation, the scour protection remained effective throughout the entire experimental test (all 3000 waves), showing apparent static behaviour during the first two conditions tested and a dynamic behaviour in the remaining ones. However, for the J_WC_15.5 and J_WR_14 tests, the protection nearly failed in the back-pile region (see Figures in Appendix IV). For the jacket test set, the measured damage number did not fall within the static and failure thresholds defined by De Vos *et al.* (2012). Therefore, the protection was classified based on a visual assessment.

The highest S_{3D} values in this study were associated with higher wave heights and longer wave periods, as noted by Zhang *et al.* (2025). When analysing the damage distribution near the pile reinforcement region in jacket-only configurations, using measures such as the mean damage, the 90th or 95th percentile, the results showed that the front pile area was more affected by scour when exposed to waves with shorter peak periods. For larger T_p values, the same measures indicated that the most affected areas shifted to the rear-pile zone (Table 4), an observation also reported by Zhang *et al.* (2025), except for the J_WI_14 test, where damage had a similar distribution in value but with a slight edge to one of the front piles.

The observed shift in the most damaged zone from the front to the rear-pile region with increasing wave height and peak period can be attributed to a change in the dominant scour mechanism. Under lower H_s and T_p conditions, damage is mainly caused by local horseshoe vortices forming at the front piles, while rear piles are protected by a sheltering effect from upstream structural elements. Conversely, under more energetic conditions, the interaction between flow and the jacket's structural elements becomes stronger. This leads to more intense wake vortices shedding, more prominent horseshoe vortices, and a notable increase in streamline contractions between the legs and around the edge of the protection in the rear

pile region. The resulting flow acceleration, along with increased turbulence and shear stresses in the wake of the scour protection, explains the higher damage rate observed in the jacket foundation's rear section.

Table 29 – Most affected areas vs. peak period (T_p).

Test	T_p [s]	Most Affected Region	
		Front Piles	Rear Piles
J_WC_7	1.471	x	
J_WC_11	[1.613–1.695]	x	
J_WC_15.5	1.887		x
J_WI_14	[2.083–2.174]	x	
J_WR_14	2.222		x
JH_WC_7	1.471	x	
JH_WC_11	1.695	x	
JH_WC_15.5	1.961	x	
JH_WI_14	2.273	x	
JH_WR_14	2.273	x	

In contrast, the hybrid jackets consistently exhibited high damage rates at the front piles across all test conditions. Test JH_WC_15.5 revealed severe damage rates to both the front and rear piles, with the front pile more severely affected. These findings suggest that integrating the WEC fundamentally changes the scour distribution pattern, may reduce the impact of the peak period, and may lead to increased scour rates at the frontal areas.

A noticeable disparity was observed between $S_{3D,measured}$ and $S_{3D,predicted}$, as shown in Table 27, using the formula developed by De Vos *et al.* (2012). Overall, the predicted values tend to underestimate scour for both the jacket and the hybrid jacket. The discrepancy was even more significant in the case of the hybrid jacket structures. This underestimation may suggest that the formula is not well-suited for foundations with complex geometries, fails to account for nonlinear elements related to intricate hydrodynamics in hybrid systems, or stems from inherent differences in the measuring sub-areas approach between the two methods. Furthermore, the differences between the measured and predicted values highlight fundamental methodological distinctions. The first method employs fixed sub-areas matching the monopile cross-section, averages scour depth over larger regions, and ignores the protection thickness, making it suitable primarily for circular geometries. Conversely, the second method utilises movable, overlapping sub-areas of predefined size, allowing for more detailed damage assessment.

5.3. OVERLAPPING GRID RATIO

The damage assessment method originally established by Fazeres-Ferradosa *et al.* (2020) was based on the radial symmetry of monopile foundations and circular scour protections. While effective for circular cross-sections, this radial approach lacks the flexibility needed for the complex, non-circular geometries used in this study (*e.g.*, multi-pile foundations and square protection layouts). To address this geometric limitation, a new version of the algorithm was developed, shifting from a structure-centred radial grid to a linear, vertex-initiated topology (Figure 61). This method creates the mesh progressively, row by row, starting from the boundary of the protection, ensuring uniform overlapping distances throughout the domain. Additionally, to handle discretisation challenges near the piles' interfaces, local mesh refinement can be applied by reducing the sampling sub-areas, thereby increasing the resolution and

accuracy in these critical zones. As noted earlier, to the authors' knowledge, this marks the first successful generalisation of the overlapping-circle method to complex scour protection-foundation configurations. Further insight into the adaptation process to develop the new version of the overlapping-circle method is provided in Chapter 6.

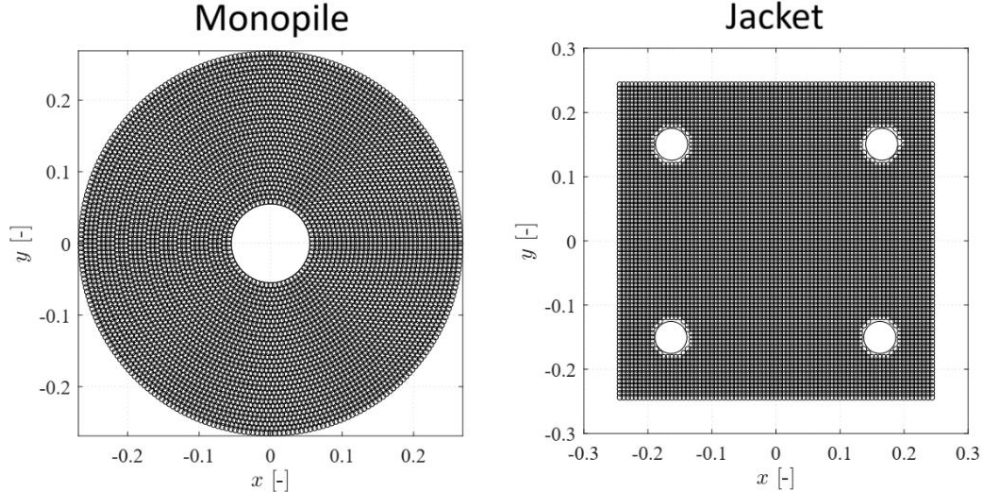


Figure 61 – Overlapping-circle method sub-area arrangement for a monopile and a 4-leg jacket ($A_{sub}=4D_{n50}^2$).

Due to the sensitivity of the damage number to the grid ratio, an analysis of the $S_{3D,max}$ variation across different $\eta_{S3D,grid}$ was conducted. Additionally, since the maximum damage number corresponds to the value at the deepest point within the scour protection, a statistical preview of the standard deviation and the 95th percentile (P_{95}) is provided to evaluate potential convergence behaviour. A broad range of grid ratios and A_{sub} values, including the jacket pile cross section, A_{pile_jacket} to D_{n50}^2 – including several other arrangements (Figure 62) of armour layer units ($nD_{n50} \times nD_{n50}$ or $nD_{n50} \times mD_{n50}$).

Modifying the grid ratio influences the number of elements analysed, leading to notable variations in $S_{3D,max}$ and significant differences in measurement accuracy near the piles. Higher grid ratios, which correspond to smaller A_{sub} and more elements analysed, produced scour representations that closely match the detailed topography obtained from DTMs. Conversely, lower grid ratios, associated with larger A_{sub} and fewer elements analysed, tend to be less accurate and struggle to represent overlapping elements near the corners and around the piles.

Figure 63 demonstrates this effect for the J_WI_14 case (3000 waves), where a marked variation in the damage number was observed across different ratios: with $A_{sub}=A_{pile_jacket}$, largest sub-area and fewer elements analysed resulted in a $S_{3D,max}=3.21$, whereas with $A_{sub}=D_{n50}^2$, smallest sub-area and higher number of analysed elements resulted in a $S_{3D,max}=5.14$, a nearly 64% increase – likely due to localized, possibly spot-specific deformation with minimal filter exposure.

Figure 64 and Figure 65 display the $S_{3D,max}$ versus $\eta_{S3D,grid}$ results shown in the Tables in Appendix IV. Both plots reveal a dependence and positive correlation between the two variables, which aligns with the findings reported by Fazeres-Ferradosa *et al.* (2020). This demonstrates that the grid ratio must be carefully selected, as it can produce a wide range of outcomes, potentially leading to different interpretations of scour protection behaviour. The results highlight the importance of developing a universal failure criterion for evaluating scour protection performance.

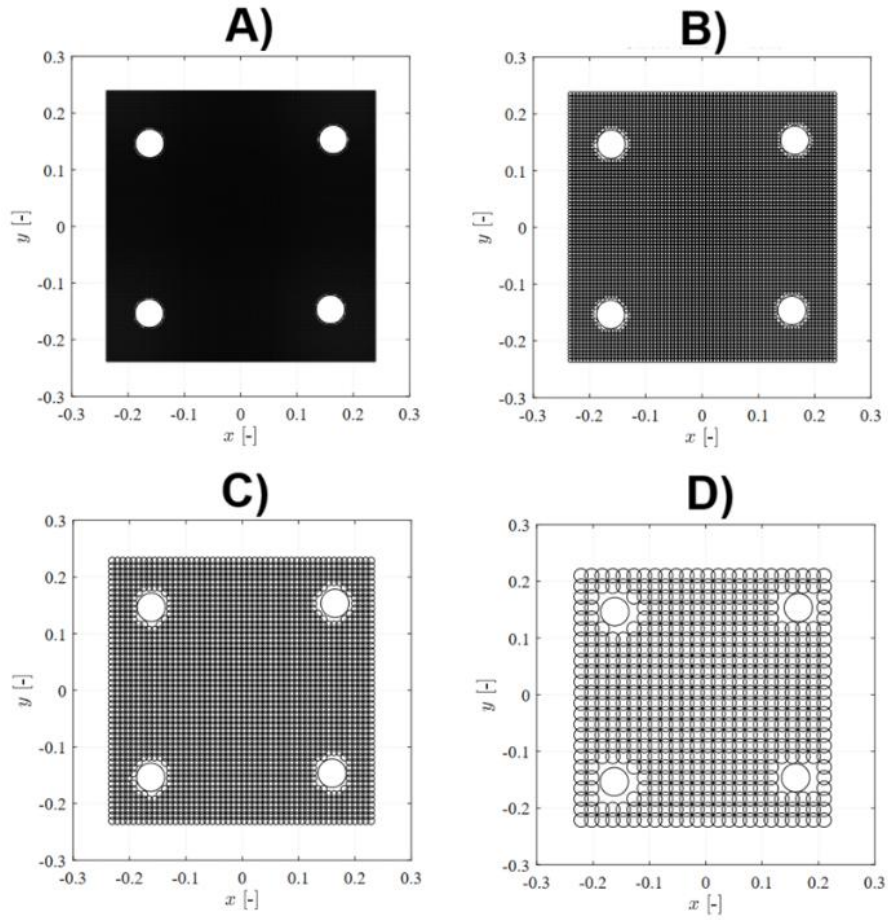


Figure 62 – Overlapping-circle sub-area arrangement for different grid ratios and sub-areas: (A) $\eta_{S3D,grid}=1$, $A_{sub}=D_{n50}^2$; (B) $\eta_{S3D,grid}=1/4$, $A_{sub}=4D_{n50}^2$; (C) $\eta_{S3D,grid}=1/9$, $A_{sub}=9D_{n50}^2$; (D) $\eta_{S3D,grid}=2.78 \times 10^{-2}$, $A_{sub}=A_{pile_jacket}$.

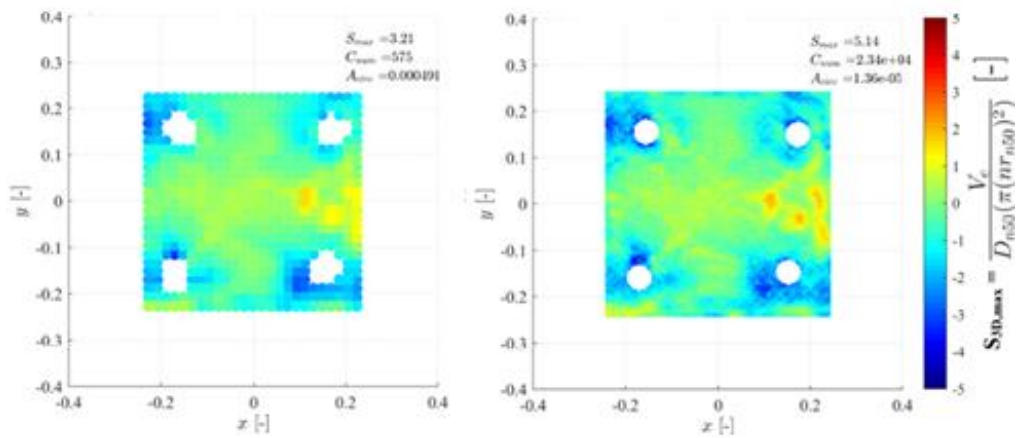
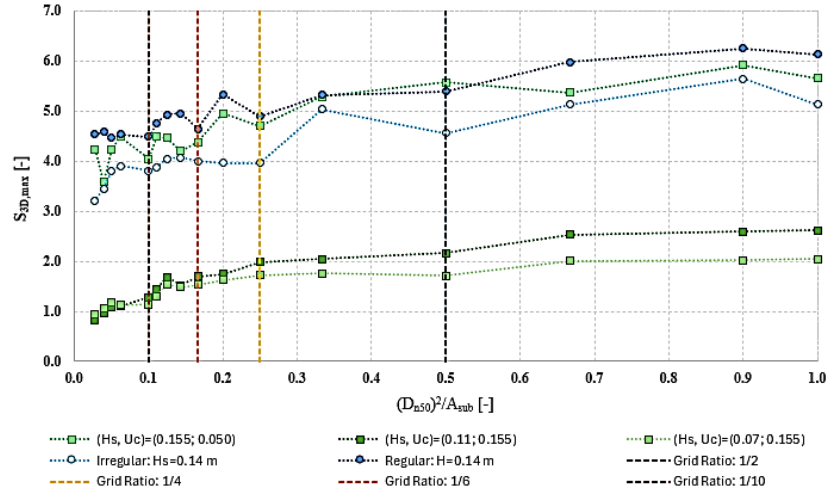
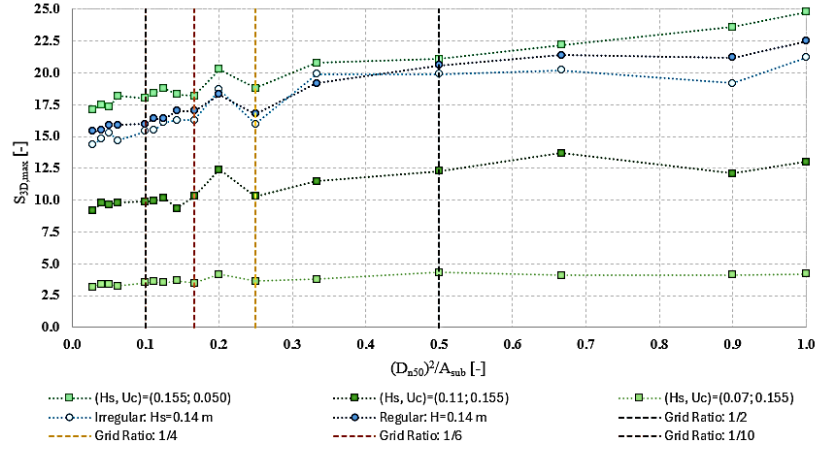


Figure 63 – Influence of $\eta_{S3D,grid}$ on damage number: $\eta_{S3D,grid}=2.78 \times 10^{-2}$, $A_{sub}=A_{pile_jacket}$, $S_{D,max}=3.49$ (left); $\eta_{S3D,grid}=1$, $A_{sub}=D_{n50}^2$, $S_{D,max}=5.14$ (right).

Figure 64 – Variation of $S_{3D,max}$ with $\eta_{S3D,grid}$ (jacket tests).Figure 65 – Variation of $S_{3D,max}$ with $\eta_{S3D,grid}$ (hybrid jacket tests).

The $S_{3D,max}$ growth for the jacket foundation in Figure 64 follows a logarithmic trend from $\eta_{S3D,grid}=2.78 \times 10^{-2}$ ($A_{sub}=A_{pile_jacket}$) to $\eta_{S3D,grid}=1/4$ ($A_{sub}=4D_{n50}^2$). For the highest wave conditions tested, the damage number shows erratic variation within this interval. From $\eta_{S3D,grid}=1/4$ to $\eta_{S3D,grid}=1$ ($A_{sub}=D_{n50}^2$), $S_{3D,max}$ generally follows a linear trend. The hybrid jacket (Figure 65) shows a linear increase in $S_{3D,max}$, mainly due to severe damage to the scour protection and the seabed across nearly all grid ratios and test conditions. For both foundations, a localised spike occurs at $\eta_{S3D,grid}=1/5$ ($A_{sub}=5D_{n50}^2$ in most tests).

Based on the results, the most suitable range of grid ratios and sub-areas values for accurately determining the protection's S_{3D} in foundations and protections with complex geometry appears to be within $\eta_{S3D,grid}=1/8$ ($A_{sub}=8D_{n50}^2$) to $\eta_{S3D,grid}=1/4$ ($A_{sub}=4D_{n50}^2$), excluding $\eta_{S3D,grid}=1/5$ ($A_{sub}=5D_{n50}^2$). The ideal range for monopiles and common scour protection geometries, as determined in Chapter 4, is between $\eta_{S3D,grid}=1/6$ ($A_{sub}=6D_{n50}^2$) and $\eta_{S3D,grid}=1/4$ ($A_{sub}=4D_{n50}^2$), again, except for $\eta_{S3D,grid}=1/5$ ($A_{sub}=5D_{n50}^2$). Both findings are consistent with previous research by Fazerer-Ferradosa *et al.* (2020), which supports the adaptability of the overlapping method to various foundation and scour protection

geometries. However, since low grid ratios, *i.e.*, high A_{sub} values, pose difficulties in accurately representing and overlapping elements near corners and around piles in complex foundations and squared protections, $\eta_{S3D,grid}=1/4$ ($A_{sub}=4D_{n50}^2$) appears to be the most appropriate grid ratio and sub-area to apply regardless of the foundation and scour protection configuration. Consequently, it suggests that the failure criterion established by den Boon *et al.* (2004) may still be the most reasonable threshold to accurately identify failure.

The standard deviation (Figure 66) and the 95th percentile (Figure 67) were plotted against the jacket tests to confirm convergence behaviour across all analysed grid ratios, as $S_{3D,max}$ appears particularly sensitive to small fluctuations in $\eta_{S3D,grid}$. Up to $\eta_{S3D,grid}=1/4$, both metrics exhibit a slight logarithmic trend, followed by a nearly linear trend beyond this point. Generally, there is minimal variation in grid ratios above $1/6$, and even above $1/10$ in four of the five conditions tested at the 95th percentile.

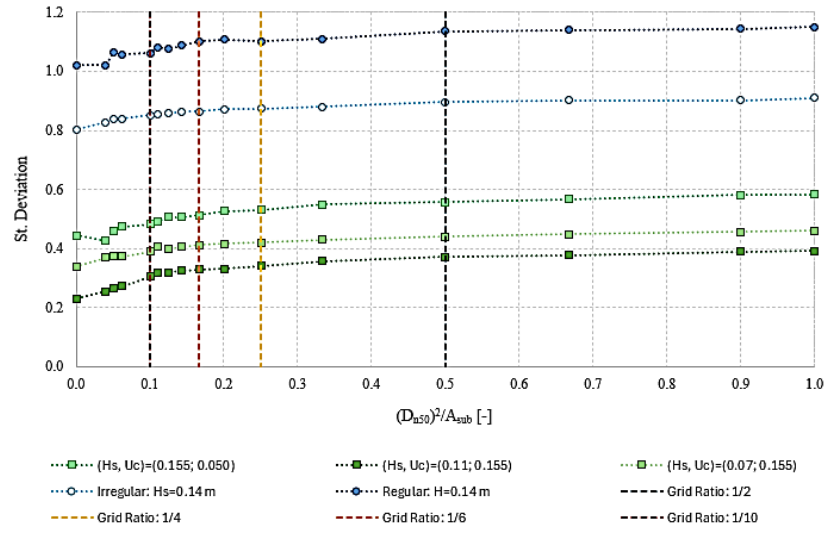


Figure 66 – Variation in the standard deviation with $\eta_{S3D,grid}$ (jacket tests).

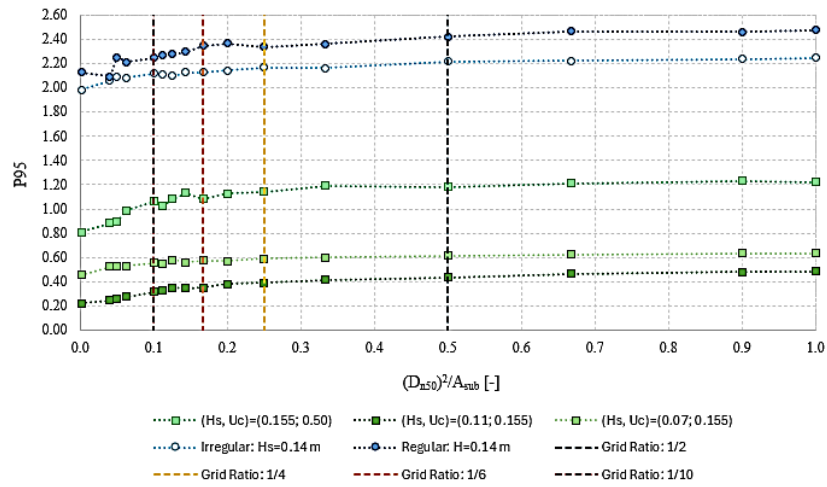


Figure 67 – Variation in the standard deviation with $\eta_{S3D,grid}$ (jacket tests).

The development of these statistical metrics with respect to the grid ratio shows considerably less variability than $S_{3D,max}$, offering a clear indication of damage convergence. Both metrics are useful since they are less affected by small fluctuations in the scour pattern, such as localised deformations or the displacement of a single armour layer unit. Therefore, incorporating the standard deviation and 95th percentile assessment ensures a more reliable damage evaluation that does not depend solely on the damage number, while verifying that convergence is achieved for the chosen grid ratio and the corresponding sub-area. Overall, the overlapping-circle method seems to have a negligible effect on the convergence of these two statistical parameters.

5.4. ALTERNATIVE DAMAGE METRICS

The damage number was defined by De Vos *et al.* (2012) as the number of protection layers lost to scour, normalised by D_{n50} , with static and failure limits of $S_{3D,static} > 0.25$ and $S_{3D,failure} > 1.0$, respectively. Consequently, observing a $S_{3D,failure} > 1.0$ for a model thickness of $t_s = 5D_{n50}$ around the piles, or $t_s = 3D_{n50}$ in the remaining area, may not accurately reflect failure, as it only indicates a loss of a layer. Conversely, the method developed by Fazeres-Ferradosa *et al.* (2020), which applies the failure criterion from den Boon *et al.* (2000), suggests that filter exposure and failure only occur when the specific condition $S_{3D} \times D_{n50} \geq t_s$ is met.

In this context, Chapter 4 demonstrated that comparing S_{3D} with t_s as a function of D_{n50} provides further insights into the actual state of protection. While it is necessary to consider some degree of uncertainty, establishing the failure limit as a range around $S_{3D,failure} = n_s$ for $t_s = n_s \times D_{n50}$ is recommended. By adopting this approach, comparing damage number values against a failure threshold of $S_{3D,failure} = 5.0$ (Table 30) enables a more precise assessment of the protection's behaviour, especially when using the overlapping method, and offers a better understanding of the physical significance of the damage number.

Table 30 – $S_{3D,max}$ comparison with static and failure thresholds proposed based on the protection's thickness.

Test	$S_{3D,max}$	Static Threshold	Failure Threshold
J_WC_7_1000	1.61	$S_{3D} = 0.25$ (De Vos <i>et al.</i> , 2012)	$S_{3D} = 5.0$ (based on n_s)
J_WC_7_2000	1.76		
J_WC_7_3000	1.72		
J_WC_11_1000	1.67		
J_WC_11_2000	1.80		
J_WC_11_3000	1.98		
J_WC_15.5_1000	3.27		
J_WC_15.5_2000	4.62		
J_WC_15.5_3000	4.71		
J_WI_14_1000	3.85		
J_WI_14_2000	3.67		
J_WI_14_3000	3.96		
J_WR_14_1000	2.83		
J_WR_14_2000	3.72		
J_WR_14_3000	4.90		
JH_WC_7_1000	3.02		
JH_WC_7_2000	3.01		
JH_WC_7_3000	3.65		
JH_WC_11_1000	10.40		
JH_WC_15.5_1000	19.10		
JH_WI_14_1000	16.00		
JH_WR_14_1000	16.80		

Although Chapter 4 suggested setting the static limit to 0.25, consistent with the threshold proposed by De Vos *et al.* (2012), further analysis of the results, particularly for the J_WC_7 and J_WC_11 cases (classified as static), revealed that the measured damage number values exceeded this threshold. This discrepancy highlights the need to define both static and failure limits relative to the protection thickness, not just the last one. The $S_{3D,static}=0.25$ was suitable for monopiles covered with circular protections with $t_s=2.5D_{n50}$. However, for complex structures and scour configurations or thicknesses, a fixed threshold has proven unsuitable. This supports the view that both boundaries for classifying scour protections should be set as a specific percentage of the t_s value and/or defined by a range, rather than a single fixed number.

The $\Delta S_{3D}/n_s$, introduced by De Schoessiter *et al.* (2014), offers an alternative to the limitations of the fixed sub-areas approach by De Vos *et al.* (2012). Although effective at describing how quickly damage develops, the results presented in Chapter 4 showed that it does not reliably indicate how close the protection is to failure, and that overlapping ranges were observed across the three behavioural categories. Similarly, for riprap protection, the conventional S/D ratio is of limited significance, as it poorly reflects deformation or the loss of armour layers. As a result, the suggested S/t_s and S_{3D}/n_s ratios are employed, providing a more robust physical correspondence to the protection's overall damage state.

The following threshold ratios were previously defined as:

- **Failure:** $S_{3D}/n_s > 1$ or $S/t_s > 1$;
- **Dynamic Protection:** $0.25 < S_{3D}/n_s$ or $S/t_s < 1$;
- **Static Protection:** $0 < S_{3D}/n_s$ or $S/t_s < 0.25$;
- **Recovery (Sediment Accretion):** $S_{3D}/n_s < 0$ or $S/t_s < 0$;

The proposed limits for the two ratios were used to assess the scour protection. Failures identified visually or by the overlapping-circle method corresponded to S_{3D}/n_s or $S/t_s > 1.0$, while dynamic protections remained below these thresholds (Table 31).

Table 31 – Scour depth (S), S_{3D}/n_s , and S/t_s comparison with proposed failure threshold.

Test	S [mm]	S/t_s or S_{3D}/n_s	Static Threshold	Failure Threshold
J_WC_7_1000	5.95	0.32	0.25	1.0
J_WC_7_2000	6.50	0.35		
J_WC_7_3000	6.36	0.34		
J_WC_11_1000	6.17	0.33		
J_WC_11_2000	6.65	0.36		
J_WC_11_3000	7.32	0.40		
J_WC_15.5_1000	12.09	0.65		
J_WC_15.5_2000	17.08	0.92		
J_WC_15.5_3000	17.41	0.94		
J_WI_14_1000	14.23	0.77		
J_WI_14_2000	13.56	0.73		
J_WI_14_3000	14.64	0.79		
J_WR_14_1000	10.46	0.57		
J_WR_14_2000	13.75	0.74		
J_WR_14_3000	18.11	0.98		
JH_WC_7_1000	11.16	0.60		
JH_WC_7_2000	11.12	0.60		
JH_WC_7_3000	13.49	0.73		
JH_WC_11_1000	38.44	2.08		
JH_WC_15.5_1000	70.59	3.82		
JH_WI_14_1000	59.14	3.20		
JH_WR_14_1000	62.09	3.36		

However, for the static J_WC_7 and J_WC_11 tests, the conditions S_{3D}/n_s or $S/t_s < 0.25$ were not met, with most values roughly around 1/3. These findings suggest that, although both ratios effectively capture dynamic or failure behaviour, the static limit should be reconsidered or adjusted to account for complex structural and varying protection configurations. Ultimately, the overlapping approach proves to be highly effective for visualising and measuring scour, providing a consistent tool for damage assessment and identification. Additionally, the ratio-based indicators, such as S_{3D}/n_s and S/t_s , show potential for developing adaptable design frameworks, thereby improving the reliability of scour protections in complex hydrodynamic environments.

5.5. KC AND U_{cw} EFFECTS

The analysis of damage evolution with respect to U_{cw} ratio shows that S_{3D} values tend to increase as U_{cw} decreases (Table 27 and Figure 68), contrary to the findings of Chen *et al.* (2025), providing further evidence of the complexity of the wave-current regime and underscoring the need to consider the KC number's impact. In fact, the trend mainly reflects the hydrodynamic conditions during testing: higher U_{cw} tests featured reduced wave heights and increased current velocities, while lower U_{cw} values involved more energetic wave conditions, specifically, higher wave heights with less influence from current.

As noted by Zhang *et al.* (2025), increased wave energy significantly amplifies scour rates. Further examination of tests with comparable KC numbers (J_WC_15.5, J_WI_14, and J_WR_14) indicates that the J_WC_15.5 test ($KC=15.41$, $U_{cw}=0.19$, $S_{3D,max}=4.71$) showed damage levels that were slightly superior or similar to those recorded in the J_WI_14 test ($KC=16.30$, $U_{cw}=0$, $S_{3D,max}=3.96$) and J_WR_14 test ($KC=17.54$, $U_{cw}=0$, $S_{3D,max}=4.90$), respectively. This small sample agrees with findings reported by Chen *et al.* (2025) and Schendel *et al.* (2020), for jacket and monopile foundations, respectively, that a slight superimposition of a current load can increase scour depths.

Overall, the results shown in Table 27 and Figure 68 consistently indicate that damage increases with higher KC values, regardless of the hydrodynamic regime, as it is directly linked to the amplification of shear stress and vortex shedding around the foundation, which are the main causes of scour.

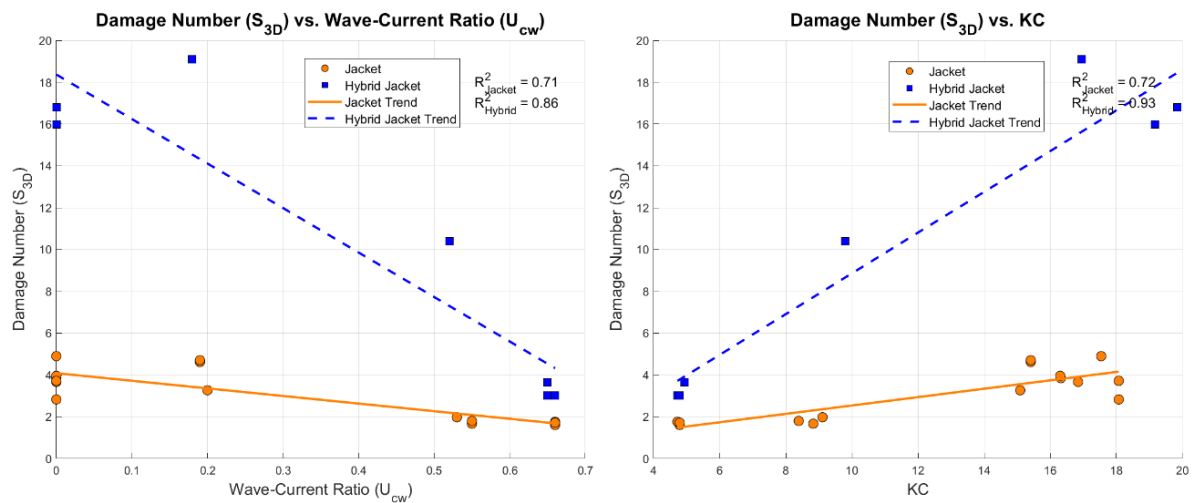


Figure 68 – S_{3D} vs. U_{cw} ratio and KC number (jacket and hybrid jacket test).

When comparing the jacket-only configurations with the hybrid jackets, the effect of a lower U_{cw} ratio was found to be even more pronounced for the hybrid structures. Deformation is greatly affected by intensified oscillatory flow patterns and increased shear stresses (as captured by the KC number). The higher damage rates associated with elevated KC and reduced U_{cw} values are attributed to distinctive hydrodynamic interactions induced by the OSWEC paddles' oscillatory motion. In highly energetic, wave-dominated regimes, this motion results in significant fluctuations in local flow velocities and pore pressures, thereby enhancing bed shear stress, turbulence, upward and downward pressure cycles, and flow acceleration near the structure. These dynamic interactions act as an additional scour-driving mechanism, substantially increasing sediment mobilisation compared to conventional jacket foundations under similar conditions.

5.6. WAVE TRANSMISSION AND WAVE REDUCTION COEFFICIENTS

The main aim of this experimental study was to assess damage to the scour protection of two foundation types. However, adding a WEC to convert a jacket foundation into a hybrid jacket revealed substantial changes in flow patterns and hydrodynamic behaviour. Since the study did not focus on the mechanical power performance of the WEC, parameters such as captured energy efficiency or power per unit front were not assessed. Instead, simplified hydrodynamic interactions – namely the wave transmission coefficient (K_T), which compares seaside and leeside wave heights for each test, and the wave reduction coefficient (K_{Red}), which compares wave heights between jacket-only and hybrid jacket configurations under similar conditions – were used to measure the influence of both foundations on wave attenuation.

For jacket-only tests, the K_T values remained slightly above 100% (Table 32), with deviations ranging from 1.4% to 7.5%. Although the upper truss was expected to obstruct flow and slightly reduce leeward wave height, the structure's open cross-section likely facilitated near-complete wave propagation, confirming its limited wave-sheltering capacity. In contrast, the hybrid jacket with the integrated WEC achieved a notable reduction in K_T , particularly at higher wave heights, with up to 27% attenuation on the leeward side. These reductions were attained using a simplified mechanical actuation system for the WEC paddles, suggesting that a fully operational PTO system could further improve attenuation. The observed trends are consistent with the findings described in Chapter 4, reinforcing that hybridisation can be effectively extended not only to monopiles but also to more complex foundation geometries. Such configurations enhance dissipation, increase wave absorption, and lower transmitted wave energy. However, a trade-off was identified: the hybrid jacket led to higher turbulence levels and greater flow contraction, contributing to the significant increase in damage observed at the scour protection system.

Regarding the wave reduction coefficient, most seaside K_{Red} values for the hybrid jacket (Table 33) were negative, indicating local wave amplification of up to 10%. This effect is likely caused by intense scour erosion that lowered the seabed, increasing local water depth and enabling larger, non-breaking waves. Conversely, the leeside K_{Red} values consistently showed significant reductions in wave height – up to 33%, in line with the results reported in Chapter 4. These findings highlight the potential of WECs as multifunctional components in offshore infrastructure, serving not only as renewable energy devices but also as protective elements that reduce wave energy and coastal erosion (Fazeres-Ferradosa *et al.*, 2019b). However, the optimisation and strategic integration of PTO systems remain essential to address the scour aggravation associated with WECs. While the WEC decreased the transmitted wave height, it simultaneously increased scour damage to the armour layer. This outcome suggests that both the paddle's rotational angle and its clearance from the seabed are vital design parameters to lessen excessive scour or structural damage.

Table 32 – Wave transmission coefficient (K_T) for jacket and hybrid jacket tests.

Test	No. of Waves	K_T (%)
J_WC_7_1000	1000	102.9
J_WC_7_2000	1000	104.4
J_WC_7_3000	1000	101.4
J_WC_11_1000	1000	105.0
J_WC_11_2000	1000	104.9
J_WC_11_3000	1000	104.7
J_WC_15.5_1000	1000	100.7
J_WC_15.5_2000	1000	100.0
J_WC_15.5_3000	1000	100.0
J_WI_14_1000	1000	102.9
J_WI_14_2000	1000	105.2
J_WI_14_3000	1000	100.0
J_WR_14_1000	1000	104.3
J_WR_14_2000	1000	106.5
J_WR_14_3000	1000	107.5
JH_WC_7_1000	1000	95.6
JH_WC_7_2000	1000	97.1
JH_WC_7_3000	1000	93.0
JH_WC_11_1000	1000	82.9
JH_WC_15.5_1000	1000	73.4
JH_WI_14_1000	1000	73.9
JH_WR_14_1000	1000	78.2

Table 33 – Wave reduction coefficient (K_{Red}) for monopile and hybrid monopile tests.

Test	No. of Waves	Offshore K_{Red} (%)	Onshore K_{Red} (%)
J_WC_7 vs JH_WC_7	1000	1.5	9.2
	1000	-1.4	6.0
	1000	-2.8	6.1
J_WC_11 vs JH_WC_11	1000	-9.9	14.1
J_WC_15.5 vs JH_WC_15.5	1000	-5.8	29.2
J_WI_14 vs JH_WC_14	1000	-4.2	33.3
J_WC_14 vs JH_WR_14	1000	-6.1	25.2

The same conclusion was reported by Taheri *et al.* (2022), who implemented an OSWEC on the seabed as a protective element for pipelines and observed that the variation in the angle between the flap and the seabed affected scour rates. When a smaller rotational amplitude around the vertical axis was used, which limited oscillatory motion and velocity, scour depths were reduced. Regarding the converter's tip clearance, defined as the vertical distance between a rotating blade or paddle and the seabed, Chen *et al.* (2017) reported intensified scour rates up to 10–20% in extent and 30% in depth. The rate tended to increase more rapidly with smaller tip clearances, despite the equilibrium scour depth being independent of the distance to the seabed. Therefore, future research should conduct a detailed study of the effects of tip clearance on scour and on the structural resilience of scour protections for hybrid structures and marine harvesting technologies.

5.7. STANDARD VS COMPLEX FOUNDATIONS

This research conducted a comparative analysis of the results on damage counts and visual classification with those obtained for the (hybrid) monopile setup, as the test conditions and hydrodynamic scenarios

were similar. The comparison allows for a more comprehensive assessment of the structural effects on scour between these quite different foundation types.

Table 34 shows that the measured values under the least energetic hydrodynamic condition were very similar across all model configurations (jacket vs. monopile and hybrid jacket vs. hybrid monopile). Under the intermediate condition ($H_s=0.11$ m), comparable damage numbers were only recorded between the jacket-monopile pair. For the three highest wave-tested cases, the jacket/hybrid jacket configurations exhibit notably higher S_{3D} measured values compared to their monopile counterparts. These findings align with those of Chen *et al.* (2023), who studied jackets under current-only conditions, and with those of Zhang *et al.* (2025), who conducted tests under wave-only scenarios. Conversely, they differ from the results of Welzel *et al.* (2019), which involved perpendicular wave-current alignment. Since this study employed collinear wave-current and wave-only conditions, the results suggest that flow direction significantly influences sediment-structure-flow interactions, an aspect that merits further investigation.

Although differences in damage counts were observed between the studies, the visual classification of the scour protections (Table 34) showed that the characteristics of the protection setup applied to the (hybrid) jacket demonstrated overall improved performance. For the jacket, the protection withstood the full test duration, whereas in Chapter 4, failures occurred for the WC_15.5 and WR_14 tests within the first 1000 waves. A similar pattern was observed for the WC_7 test in the hybrid jacket, where the protection withstood the full 3000-wave test. In contrast, the protection used for the hybrid monopile failed prematurely. These performance enhancements can be linked to the increased protection thickness used for the (hybrid) jackets, $t_s=3D_{n50}$ across most of the footprint and locally reinforced to $t_s=5D_{n50}$ at each pile, following the recommendations proposed by Welzel *et al.* (2019b) and Sarmiento *et al.* (2021), compared to the $t_s=2.5D_{n50}$ protection tested for the (hybrid) monopiles.

Table 34 – Damage number and visual damage comparison between (hybrid) jackets and (hybrid) monopile foundations.

Test	$S_{3D,measured}$	Jacket Visual Classification	$S_{3D,measured}$	Monopile Visual Classification
WC_7	1.72	Static (3000 waves)	1.95	Dynamic (3000 waves)
WC_11	1.98	Static (3000 waves)	1.83	Dynamic (3000 waves)
WC_15.5	4.71	Dynamic (almost fails for 3000 waves)	2.87	Failure (1000 waves)
WI_14	3.96	Dynamic (3000 waves)	3.08	Dynamic (almost fails for 3000 waves)
WR_14	4.90	Dynamic (almost fails for 3000 waves)	3.18	Failure (1000 waves)
Hybrid_WC_7	3.65	Slightly dynamic (3000 waves)	3.25	Failure (2000 waves)
Hybrid_WC_11	10.40		5.38	
Hybrid_WC_15.5	19.10	Failure	9.81	Failure
Hybrid_WI_14	16.00	(1000 waves)	7.28	(1000 waves)
Hybrid_WC_14	16.80		8.55	

Nevertheless, even with the thicker armour layer, the damage numbers recorded under the more energetic wave conditions for the hybrid jacket were nearly twice those registered for the hybrid monopile. The increase in damage between the two hybrid structures aligns with the severe armour-layer damage, sediment erosion, and local seabed sinking observed beneath and around the filter layer

effects that are even more pronounced than those seen with the hybrid monopile. These findings emphasise the complex hydrodynamic interactions and heightened turbulence caused by hybrid structures, underscoring the necessity for customised scour design guidelines for hybrid and geometrically complex offshore foundations.

5.8. CONCLUSIONS

This research characterises scour in riprap-protected and hybrid jackets. The primary aim was to evaluate the performance of scour protection systems for these jackets and to clarify the governing scour mechanisms, damage progression, and hydrodynamic interactions for both types of structures. The study seeks to understand how local and global scour develop at different locations and rates under the influence of WEC. By comparing these findings with those observed for monopiles and hybrid monopiles, this work provides valuable insights to guide future research in marine harvesting technologies and offers a critical assessment of current design limitations for offshore structures with complex geometries. One notable finding from the experimental testing of protected hybrid jacket structure was that, although the WEC successfully attenuated incident hydrodynamic conditions, reducing leeward wave heights by up to 33%, the converter's oscillatory motion paradoxically intensified local scour mechanisms. The generation of complex flow patterns, specifically horseshoe vortices, lee-wake vortices, streamline contractions, and downflow, resulted in severe and irreversible damage to the scour protection. This highlights a crucial design trade-off: the energy-harvesting benefit of the WEC comes at the expense of foundation structural stability and scour protection.

Regarding the differences between the jacket and hybrid jacket structure tests, the study shows that the scour protections designed for the jackets, following the recommendations by Welzel *et al.* (2019b) and Sarmiento *et al.* (2021), have retained their structural integrity, demonstrating that both recommendations provide a solid starting point for future design guidelines. However, the results also reveal that the identical protection system used on the hybrid configuration is highly vulnerable. The protection system on hybrid jackets often fails prematurely, typically within the first 1000 waves, indicating that the WEC-flow complex relationship is a significant factor in causing irreversible damage.

As for the damage number measured for both foundations, the results show that the Equation (4) developed for monopile foundations is inadequate to capture the complexities of complex and hybrid structures, raising concerns about the feasibility and conservatism of the design principles presented by De Vos *et al.* (2012). As an alternative, the overlapping-circle methodology developed by Fazeres-Ferradosa *et al.* (2020) was successfully adapted and validated for complex foundations and non-standard scour protection geometries. It enabled an accurate quantification of the damage spatial distribution. The analysis also confirmed a strong dependence of S_{3D} on the grid ratio ($\eta_{S3D,grid}$) and the chosen sub-area size (A_{sub}), consistent with the findings reported by Fazeres-Ferradosa *et al.* (2020). The grid ratios of 1/8 and 1/4, corresponding to sub-areas of $8D_{n50}^2$ and $4D_{n50}^2$, respectively, were found to be most suitable for estimating the damage number, within a range like that registered in Chapter 4. Although the $\eta_{S3D,grid}=1/4$ ($A_{sub}=4D_{n50}^2$) was identified as the most representative for assessing protection failure, in line with the failure criterion proposed by den Boon *et al.* (2004).

Alternative metric limits, such as $S/t_s > 1.0$ and $S_{3D}/n_s > 1.0$, provided a more representative assessment of protection failure than $S_{3D, failure} > 1.0$, as proposed by De Vos *et al.* (2012). Both metrics seem closer to the experimentally observed behaviours and visual classifications attributed to each test, thus indicating

a need to reconsider the limits as a function of the protection thickness. Nonetheless, the precise S_{3D} , S/t_s , or S_{3D}/n_s value for the static-to-dynamic threshold must be redefined through further testing.

The interpretations of these results must be considered within specific experimental limitations to prevent overgeneralisation.

- **Scale effects:** the use of the Froude similitude with a 1:50 geometric scale inevitably introduces some scale effects regarding viscous forces and sediment size. While the R_e number was maintained in a range to restrain vortex shedding discrepancies, as suggested by Sumer *et al.* (1992), the scaling of granular bed material may not perfectly replicate prototype sediment transport regimes.
- **OSWEC model:** The WEC selected for the experimental study was modelled as a simplified oscillating paddle system. While macroscopically this reproduces the potential effects and influences of the device in enhancing flow and scour mechanisms, it does not fully capture the real effects of damping and control strategies of a full-scale device with a fully functional PTO system.

Overall, the authors believe this study advances a broader understanding of hydrodynamic interactions in complex and hybrid offshore structure, underscoring the need to update existing scour-protection design frameworks. Although based on a limited dataset, the results clearly show the importance of a consistent and optimised design criterion that accounts for structural complexities, dynamic load interactions, and energy-harvesting components. These approaches are vital to ensure resilient, efficient, and protective solutions are continuously developed for future offshore and marine renewable infrastructure.

The following points summarise the key contributions of this research:

- **Scour protection applied to a hybrid jacket-WEC system:** comparative evaluation of the S_{3D} between a jacket and a hybrid jacket structure.
 - **OSWEC can intensify damage in hybrid structures:** Results demonstrated that paddle-based WECs intensify scour due to the influence of the paddle's oscillatory motion, thereby enhancing turbulence and flow patterns, despite its capacity to attenuate wave heights up to 33%.
- **Overlapping-circle 3D method implemented to a complex geometry foundation:** demonstration of the effectiveness and adaptable capability of the overlapping-circle method developed by Fazeres-Ferradosa *et al.* (2020) when implemented to a jacket (hybrid) foundation.
 - **Modification of the damage quantification technique to fit complex geometries:** The Fazeres-Ferradosa *et al.* (2020) method exhibited a high-resolution scour quantification capability by accurately computing S_{3D} when applied to a structure with a higher degree of structural complexity, when compared to a monopile, and to a square scour protection (different from the typical circular shape), thereby providing valuable insights into complex and hybrid configurations. Despite the sensitivity to the grid ratio, results suggest an ideal range between 1/8 and 1/4. However, low grid ratios present some difficulties in properly representing overlapping elements near the corners and around the piles in complex foundations/protections. Therefore, the 1/4 ratio remains the most reliable, consistent with the findings disclosed by den Boon *et al.* (2004) and Fazeres-Ferradosa *et al.* (2020).

- **Scour protection design predictive formula limitations:** the study's findings raise questions about the underestimation and application of current design standards, developed primarily for monopiles, that do not account for increased flow and the structural complexity of other structures and hybrid configurations. Hybrid jackets failed prematurely, with massive damage rates, within the first 1000 waves. The results emphasise that, currently, no methodology effectively accounts for the additional loads resulting from the interaction among sediment flow, WEC, and the structure.
- **Alternative scour metrics for scour protection performance:** S/t_s and S_{3D}/n_s parameters, proposed as alternatives to better quantify and evaluate the performance of scour protections.
 - **Reliable performance to evaluate failure:** in complex offshore settings, S/t_s and S_{3D}/n_s can successfully identify when a protection is dynamic, closer to failure, and when failure occurs. These measurements shift the evaluation's focus from the foundation to the armour layer itself, providing a clearer picture of relative performance. Both indicators outperform traditional parameters such as the S/D and the $S_{3D, failure} > 1.0$ threshold. However, the static limit may need to be reconsidered, as it can be overly conservative, leading to thicker protections.
- **Framework for advancing design of hybrid offshore structures:** the research improves knowledge regarding structural effects and vortex-induced shear stress amplifications of complex foundations coupled with an oscillating surge energy converter device, to promote safer, more adaptable infrastructures for marine harvesting technologies.

To further enhance the understanding of scour processes in hybrid offshore structures, future research should strategically broaden the experimental test matrix to include a wider range of hydrodynamic conditions, alternative scour protection configurations, various WEC devices, and variations in certain structural parameters. One important aspect could involve examining the influence of hydrodynamic directionality. This experimental campaign utilised only co-directional wave-current conditions due to the facilities' limitations. While this setup generally represents the most critical loading scenario, offshore and marine environments often feature complex, multi-directional flow interactions. Therefore, the impact of transverse and counter-directional wave-current regimes on damage patterns and distribution for protected complex and hybrid structures should be investigated to determine whether the asymmetry of the incoming flow causes preferential damage zones and different S_{3D} values compared to those observed in co-directional regimes. Expanding these factors will be essential to developing comprehensive datasets that capture the full spectrum of scour and damage mechanisms in such complex, hybrid systems. These efforts could be vital for increasing knowledge and improving the next generation of design approaches and predictive models that incorporate hydrodynamic–structural coupling and energy-harvesting dynamics. Such advancements could be critical to creating safer, more efficient, and sustainable offshore solutions, ultimately supporting the transition towards a more resilient marine renewable energy sector.

6. Statistical Analysis of Damage for Complex Foundations

6.1. INTRODUCTION

The application of the overlapping-circle method to both a complex foundation and non-standard scour protection geometry required an improved framework that could fit the jacket-hybrid jacket setup described in Chapter 3. The adaptation was essential to perform the analysis presented in Chapter 5. This chapter presents how the adaptation was planned, executed, and provides a thorough statistical analysis of the results, leading to the proposal of two approaches for assessing the performance of the scour protection, both from a global and a local perspective. This research was published in Chambel *et al.* (2026b), and a summary of the developed methodology and the main findings is presented in this chapter.

6.2. METHODOLOGY

6.2.1. ADAPTATION OF THE OVERLAPPING-CIRCLE METHOD

The use of the overlapping method for a jacket foundation with non-standard square protection required modifications to the original approach developed for monopiles with standard circular protection. To manage the geometric complexity of the setup, three discretisation strategies were evaluated to identify the best mesh configuration for assessing S_{3D} distribution. A 50% overlapping distance was chosen for this study, as Fazeres-Ferradosa *et al.* (2020) found that no significant benefits are gained with methods other than the 50% overlapping distance. The conceptual approaches are shown in Figure 69:

- **Option #1 (Radial Approach):** A direct adaptation of the original method, where the radial overlapping mesh is generated outward from the piles to the protection boundary. Each pile acts as a local origin – Figure 69 (left scheme).
- **Option #2 (Trimmed Radial Approach):** A modification of option A, where the elements deviating from the target 50% overlapping distance are removed to reduce redundancy – Figure 69 (middle scheme).
- **Option #3 (Row-by-Row Approach):** A linear, row-by-row discretisation strategy maintaining a constant 50% overlapping distance across the entire protection area – Figure 69 (right scheme).

Upon evaluating the generated meshes, option #1 was considered unsuitable due to significant mesh redundancy and heterogeneity. Since the overall mesh results from multiple local meshes, each linked to a local sub-centre (jacket piles), the convergence of these grids leads to non-uniform overlapping distances, resulting in excessive computational noise and redundant calculations. Moreover, this approach does not account for the geometric boundaries of a square protection armour layer, resulting

in inadequate coverage at the edges and vertices – critical zones where edge scour often begins before spreading towards the piles.

Option #2 aimed to address these issues by filtering out sub-areas that did not fully meet the 50% overlapping distance requirement. While this significantly reduced the number of sub-areas, it still encouraged spatial heterogeneity. As shown in Figure 69, this method results in varying mesh densities, especially along the central axes of the scour protection, creating localised gaps that may affect damage distribution. As a result, this uneven distribution hinders a consistent analysis of the S_{3D} across the entire protection domain.

Ultimately, option #3 was chosen as the final configuration. This row-by-row method creates a uniform, consistent mesh that respects the specified overlapping distance globally rather than locally. It offers clear advantages, such as:

- Complete coverage of the protection's boundaries (edge and vertices).
- Easier to program and apply.
- Significant reduction in computational cost.
- Homogeneous distribution of the sub-area elements.

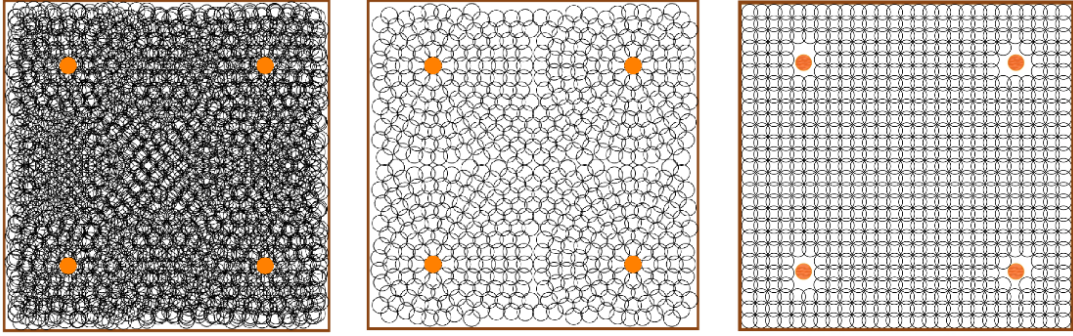


Figure 69 – Illustration of overlapping method adaptation: Left scheme - Radial mesh arrangement (starting from the piles); Middle scheme: Radial mesh arrangement with removal of elements without correct overlapping distance; Right scheme: Row-by-row mesh arrangement (starting from the protection's edge).

Nonetheless, this arrangement also has a minor disadvantage in covering the immediate area around the jacket's piles. However, it was found that this can be effectively mitigated by increasing the grid ratio, *i.e.*, reducing the sub-area size, to refine the mesh resolution. To systematically assess the influence and accuracy of mesh selection, four different resolutions were used with increasing A_{sub} values, ranging from D_{n50}^2 to the jacket pile cross-section (A_{pile_jacket}), corresponding to $\eta_{S3D,grid}$ decreasing from 1 to 2.78×10^{-2} (Figure 62). Therefore, option #3 was considered the most robust, reliable, and computationally efficient framework for quantifying damage in complex foundation and non-standard protection geometries.

6.2.2. DAMAGE CHARACTERISATION

While $S_{3D,max}$ serves as the primary indicator of damage severity, relying solely on this metric may provide an incomplete view of the protection's condition. Specifically, $S_{3D,max}$ does not account for the

spatial distribution of scour damage, which can lead to misunderstandings when comparing protections with similar damage numbers under different hydrodynamic conditions. Additionally, in practical backfilling operations, $S_{3D,max}$ does not clearly indicate where more material might be needed. Figure 70 shows cases of J_WC_15.5 ($S_{3D,max}=4.71$) and J_WR_14 ($S_{3D,max}=4.90$), both of which have nearly the same peak damage, but display markedly different damage patterns.

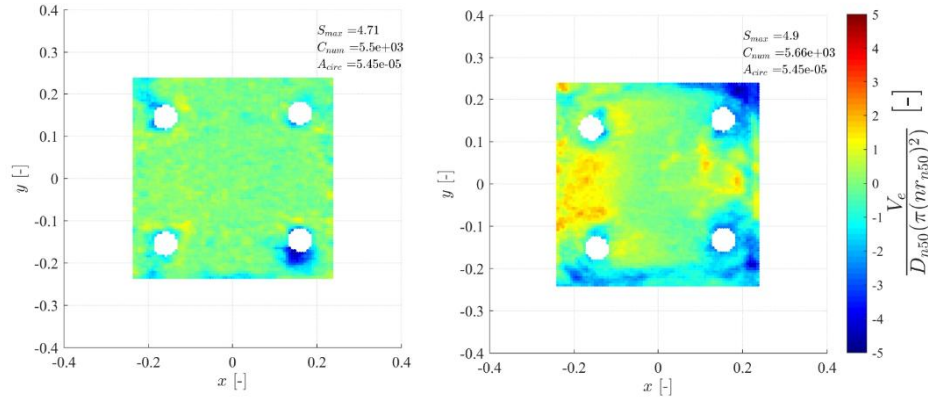


Figure 70 – Damage pattern comparison: J_WC_15.5 ($S_{3D,max}=4.71$) – left graphic; J_WR_14 ($S_{3D,max}=4.90$) – right graphic.

To address some of the limitations mentioned and to establish a reliable dataset for the following sections, a comprehensive statistical analysis of damage was conducted (see Tables in Appendix V). The analysis focused on the reinforced scour protection zones adjacent to pile A through pile D (Figure 71) – areas identified as having the highest scour exposure and the greatest risk of failure. Using the newly row-by-row method, four selected A_{sub} values were chosen to cover the four grid density ranges.

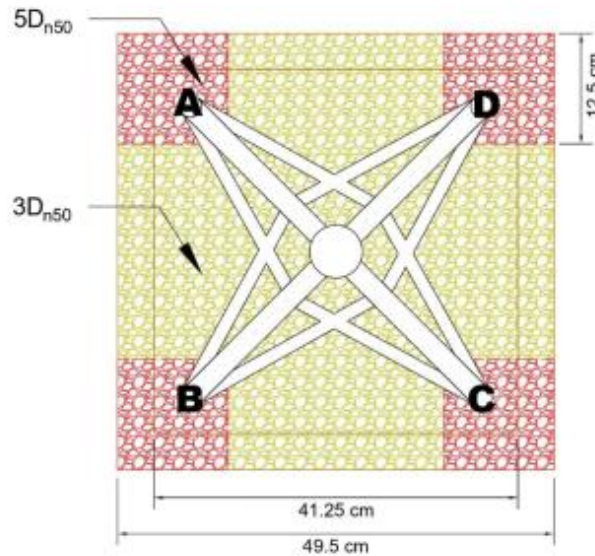


Figure 71 – Jacket foundation pile identification.

This selection simplifies the derivation of the static and failure stability threshold limits while maintaining statistical rigour across the mesh density spectrum:

- **Maximum Resolution ($\eta_{S3D,grid}=1$):** maximum grid ratio, corresponding to an $A_{sub}=D_{n50}^2=1.36\times 10^{-5} \text{ m}^2$.
- **Reference Resolution ($\eta_{S3D,grid}=1/4$):** aligning with the reference area proposed by den Boon *et al.* (2004), corresponding to $A_{sub}=4D_{n50}^2=5.45\times 10^{-5} \text{ m}^2$.
- **Intermediate Resolution ($\eta_{S3D,grid}=1/9$):** provides a data point between the reference and minimum resolution, with an $A_{sub}=9D_{n50}^2=1.23\times 10^{-4} \text{ m}^2$.
- **Minimum Resolution ($\eta_{S3D,grid}=2.78\times 10^{-2}$):** the lowest grid ratio, corresponding to an $A_{sub}=A_{pile_jacket}=4.91\times 10^{-4} \text{ m}^2$.

For the selected A_{sub} , the following statistical metrics were calculated to better describe the damage distribution: maximum ($S_{3D,max}$), mean ($S_{3D,mean}$), minimum ($S_{3D,min}$), standard deviation (σ_{S3D}), skewness, excessive, kurtosis, and the upper-bound percentiles – 99th Percentile (P_{99}), 95th Percentile (P_{95}), and 90th Percentile (P_{90}). Finally, the behaviour classification for each pile area was performed based on the obtained results, and the visual assessment of the photographic record was collected during the experimental campaign.

6.2.3. DEFINITION OF FAILURE-STATIC THRESHOLDS

As reported by Fazeres-Ferradosa *et al.* (2020), selecting the grid ratio is a crucial aspect of the overlapping-circle method and can inherently influence the damage number. Furthermore, applying the method to complex foundations and non-standard scour protection geometries introduces additional uncertainty regarding both the choice of the grid ratio and the static-failure threshold limits that define each potential state of the scour protection (static, dynamic, or failure). To maintain the diagnostic value of high- and low-resolution meshes without producing false positives for failure, a calibration procedure is suggested to determine and update the $S_{3D,failure}$ and $S_{3D,static}$ thresholds based on $\eta_{S3D,grid}$ and A_{sub} selection.

The process should follow a five-step approach:

- **Step 1: Damage Classification and Ranking:** Each pile area should be classified and ranked based on the results from the S_{3D} value of the reference resolution supported by a visual assessment.
- **Step 2: Estimation of Failure Threshold:** Based on the subset of piles identified as “Dynamic (Close to Failure)”, the failure threshold estimation ($S_{3D,FTE}$) is obtained as the arithmetic mean of the damage numbers obtained for each resolution.
- **Step 3: Determination of Correction Factor (C_f):** To account for minor deviations from the theoretical target, a correction factor (C_f) should be established, as the ratio between the failure threshold estimation ($S_{3D,FTE}$) and the theoretical threshold ($S_{3D,failure=n_s}$), for the reference scenario ($4D_{n50}^2$) – Equation (23).
- **Step 4: Failure Threshold Correction:** For the non-reference resolutions, the final failure thresholds should be updated ($S_{3D,failure}=S_{3D,FTE}/C_f$) to consider mesh-related over- and underestimations.
- **Step 5: Estimation of Static Threshold:** In the absence of a distinct reference for the static threshold for complex foundations and non-standard protection geometries, a static limit

($S_{3D,static}$) should be calibrated as the mean value using the data points identified as “Static (Close to Dynamic)”. A static threshold ratio (λ_{static}) is then computed as in Equation (24) for each individual resolution. The ratio quantifies the static-dynamic transition point as a normalised proportion of the failure threshold.

$$C_f = \frac{S_{3D,FTE}}{S_{3D,failure}} \quad (23)$$

$$\lambda_{static} = \frac{S_{3D,static}}{S_{3D,failure}} \quad (24)$$

Ideally, this calibration process should be validated using an extensive dataset that covers a wide variety of hydrodynamic conditions and scour protection features. This will enable the proper standardisation of both the static and failure thresholds across different mesh resolutions, thereby fine-tuning the S_{3D} ranges for specific protection behaviours and damage.

6.3. STATISTICAL ANALYSIS

The $S_{3D,max}$ analysis highlights a strong correlation between the maximum damage number and the intensity of the hydrodynamic conditions (J_WC_15.5, J_WI_14, and J_WR_14). Under lower energetic conditions, $S_{3D,max}$ values remained relatively small. Figure 64 summarises the relationship between the damage number and the grid ratio, showing a positive correlation between the two variables – consistent with the findings of Fazerres-Ferradosa *et al.* (2020). Consequently, it can be generalised that the grid ratio selection must be carefully considered when assessing the overall condition of the scour protection, as it can produce a broad range of results that lead to different interpretations.

Regarding the structural stability of the protections, all scour protections maintained their overall integrity throughout the experimental campaign, which included 3000 waves. However, distinct behavioural patterns were observed across the tests: the J_WC_7 and J_WC_11 tests mainly exhibited static behaviour, whereas the remaining tests were classified as dynamic. Nevertheless, during the J_WC_15.5 and J_WR_14 tests, the armour layer was close to failure in the rear-pile region. A more detailed breakdown of the results is available in Appendix V.

By analysing the tables of statistical results for each test (Appendix V), a clear correlation is observed between mesh resolution and $S_{3D,max}$ and $S_{3D,min}$. As A_{sub} decreases, which corresponds to a higher grid ratio and a finer mesh resolution, $S_{3D,max}$ and the absolute value of $S_{3D,min}$ (when negative indicates sediment accretion) increase. Conversely, $S_{3D,mean}$ at each pile location remains largely unchanged, showing minimal sensitivity to variations in grid ratio and the selected sub-area. Fluctuations in the extreme values can be attributed to the behaviour of σ_{S3D} , which increases with increasing grid ratio. As a result, the range between maximum and minimum values widens. Since the tighter mesh ($A_{sub}=D_{n50}^2$, $\eta_{S3D,grid}=1$) exhibits a higher standard deviation than the coarser resolution ($A_{sub}=A_{pile_jacket}$, $\eta_{S3D,grid}=2.78 \times 10^{-2}$), it generally produces higher absolute $S_{3D,max}$ and $S_{3D,min}$ values. Essentially, a coarser grid analysis reduces the occurrence of outliers and extreme values by spatially averaging data, thus smoothing the damage distribution.

The analysis of skewness and excess kurtosis reveals that both values decrease as the grid ratio diminishes, indicating a shift towards a more symmetrical distribution with values more evenly dispersed around the mean, less intermittent, and with reduced tail behaviour. This statistical smoothing enhances the applicability of the overlapping method at lower grid ratios for large- or prototype-scale monitoring, where the main aim is to capture the broad state of protection, filtering out distribution noise rather than isolated spot deformations. By removing these outliers, the analysis better aligns with the decision-making information typically needed in practical operations. However, using larger meshes also results in the loss of potentially vital information, which must be handled carefully. Suppressing extreme values may conceal specific damage spikes, making it necessary to determine whether the lost data points represent transient spot deformations that the surrounding material can compensate for or future damaged areas that will require intervention due to significant erosion.

Overall, skewness values range from -1 to 1, indicating a slight positive bias or a value close to zero. This trend shows a nearly symmetrical distribution with longer tails, reflecting the presence of outliers and extreme values on the damage (scour) side of the distribution. A notable deviation from this pattern was observed in the J_WC_11 test, where significant spatial asymmetry appeared between opposing structural features. Piles A and D showed a marked positive skewness around 2 (more erosion than accumulation), whereas pile B exhibited a clear negative skewness around -2 (more sediment accumulation). The same pile, which recorded the highest absolute skewness value, also showed the greatest variation between its extreme values, as the magnitude of accumulation ($|S_{3D,min}|=3.7$) greatly exceeded the maximum erosion ($S_{3D,max}=1.62$) at the highest grid resolution.

When trying to evaluate the statistical properties and the damage distribution symmetry characteristics for each stability regime, the following skewness values were identified (Figure 72):

- **Static Areas:** skewness $\in]-0.5, 0.5[$.
- **Static (Close to Dynamic) Areas:** skewness $\in]0, 1[$.
- **Dynamic Areas:** skewness ≈ 0 .
- **Dynamic (Close to Failure) Areas:** skewness ≈ 1 .

Interpreting the skewness correlations using Bulmer's (1979) framework revealed that both static and dynamic areas exhibit approximately symmetrical distributions. Conversely, transitional states, especially those near failure, are characterised by moderate to high skewness. Overall, the findings suggest that, physically, local scour manifests as an intermittent process, characterised by sharper deformations in localised areas or by intense spot deformations. In contrast, sediment accretion and global scour tend to be more spatially uniform.

Regarding the excess kurtosis, most of the data fall within the range of -1 to 1. Generally, the damage distribution is leptokurtic (positive kurtosis) at higher mesh resolutions, characterised by a sharper peak and heavier tails. It transitions to a platykurtic distribution (characterised by negative kurtosis) as the grid ratio decreases. This transition confirms that the damage distribution exhibits a distinct mesh-dependent tail behaviour. The positive kurtosis associated with a high-resolution mesh indicates that extreme values occur more frequently than predicted by a normal distribution, corresponding to a higher occurrence of localised severe scour sub-areas or intense accretion points that would not stand out. Conversely, when a looser mesh is employed, these extreme values are attenuated by spatial averaging, resulting in a smoother distribution.

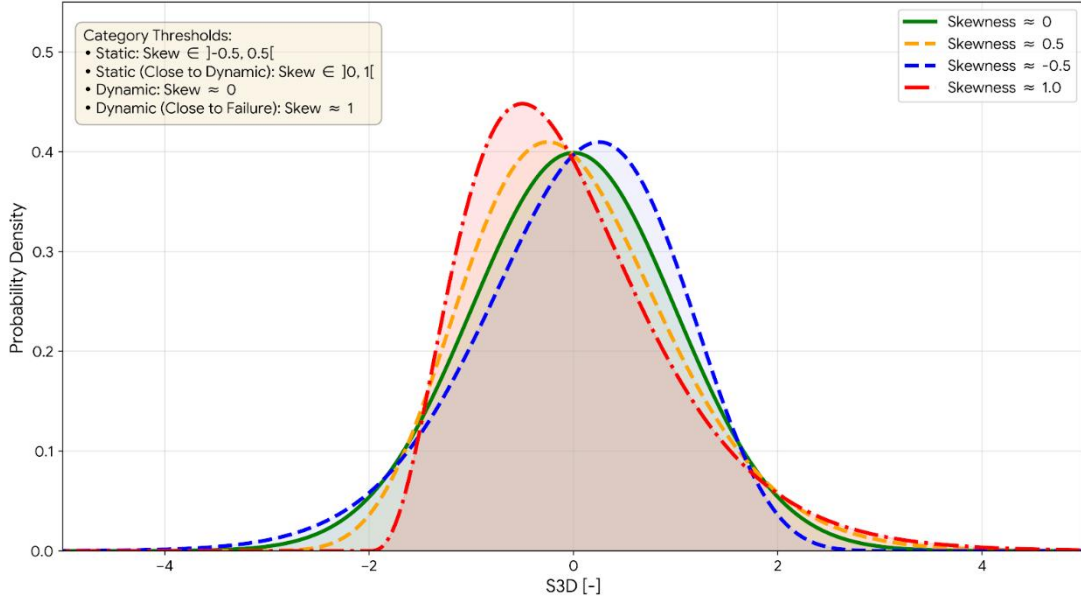


Figure 72 – Representation of skewness for different scour protection stability regimes.

A substantial deviation was once again observed in the J_WC_11 test, with high excess kurtosis values recorded: surpassing 10 for Pile B and 5 for Pile D. These elevated values aligned with the areas of greatest modifications in the scour protection; Pile B showed the highest sediment accumulation. Conversely, the maximum damage number was detected near Pile D's area. However, at the lowest grid ratio, kurtosis decreased significantly, effectively diminishing the statistical significance of these local extremes.

When comparing the absolute maximum damage value to higher-order percentiles, such as P_{99} , P_{95} , and P_{90} , a notable difference was observed, especially at high grid ratios (Figure 73). In many cases, the P_{90} and P_{95} values were more than 1 unit lower than $S_{3D,max}$, and in other cases, they were less than half the maximum value.

The differences show that $S_{3D,max}$ is often controlled by grid-scale factors and by isolated outliers or extreme values from very localised areas. This indicates that the absolute maximum damage number might be a statistically rare and non-representative value for the overall state of scour protection, rather than reflecting it. Relying solely on $S_{3D,max}$ for design and decision-making could therefore lead to overly conservative criteria for dynamic protections. However, from a structural safety perspective, these local maximum values should not be ignored, as demonstrated by near-failure zones (pile C in J_WC_15.5 and piles C-D in J_WR_14), where damage approached the maximum, even at low grid ratios.

As the mesh resolution decreases, approaching $A_{sub}=A_{pile_jacket}$, the difference diminishes: $S_{3D,max}$ decreases and approaches the P_{99} and P_{95} thresholds (Figure 74). For $A_{sub}=9D_{n50}^2$, the approximations only occur at P_{99} . In static test conditions and areas, even P_{90} nearly reaches its maximum (see piles A-C-D in J_WC_7 and piles B-D in J_WC_11). This convergence suggests that coarser meshes effectively reduce the occurrence of extreme values and outliers, leading to a more compact and statistically stable damage distribution. However, this stability may come at the expense of neglecting critical peak scour depths, potentially underestimating the severity of cumulative damage effects. Focusing on the reference resolution ($A_{sub}=4D_{n50}^2$), the statistical analysis shows that while P_{99} occasionally aligns with the $S_{3D,max}$

for the most critical areas when damage is severe, replacing $S_{3D,max}$ with the 99th percentile metric at this resolution is not justifiable for design and/or decision-making purposes. Using P_{99} does not provide sufficient optimisation or a safety margin.

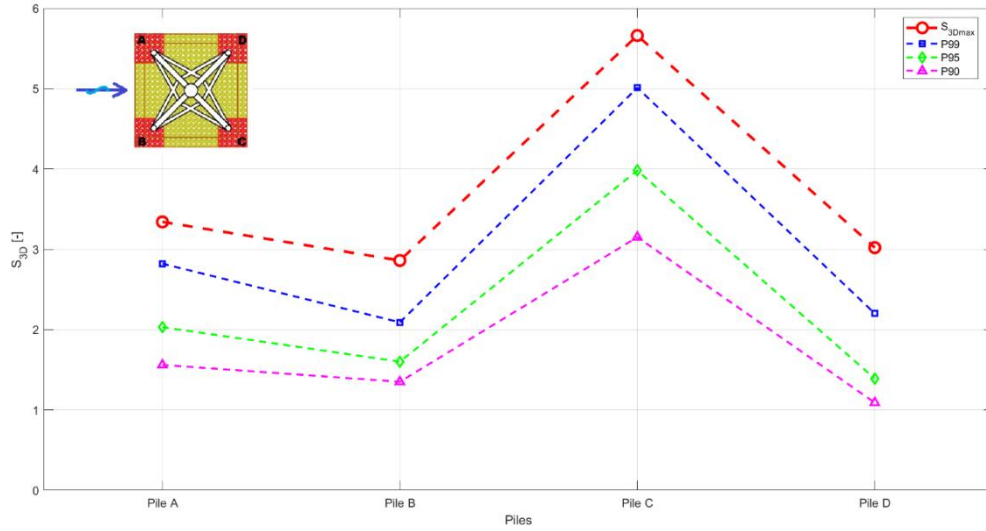


Figure 73 – Comparison of $S_{3D,max}$ vs. high-order percentiles for the highest grid ratio (J_WC_15.5 test).

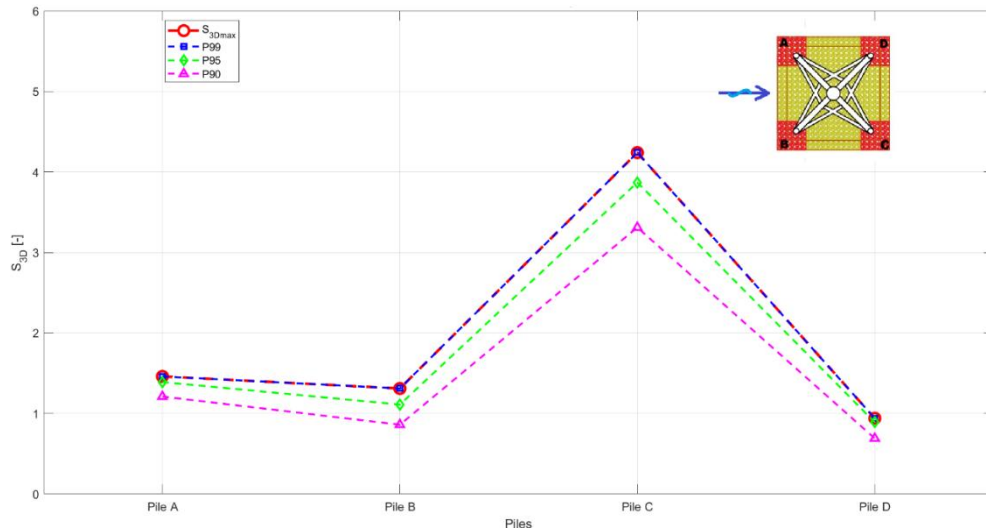


Figure 74 – Comparison of $S_{3D,max}$ vs. high-order percentiles for the lowest grid ratio (J_WC_15.5 test).

In summary, the assumptions underlying the statistical analysis indicate that the damage distribution shows intermittent, deep local deformation holes superimposed on a more widely spread pattern of erosion and accretion. The sensitivity analysis for the grid ratio demonstrates that refining the mesh increases both skewness and excess kurtosis, thereby enhancing the accuracy and detail of extreme damage values and locations. However, the disparity between $S_{3D,max}$ and the high-order percentiles in high-resolution grid meshes suggests that grid-scale singularities dominate the maximum and may lack statistical reliability. Conversely, coarser meshes act as spatial filters that mitigate tail behaviour, resulting in compact, light-tailed distributions where high percentiles tend to converge with $S_{3D,max}$.

Therefore, percentile-based metrics, such as P_{99} or P_{95} , may offer a more dependable and mesh-independent framework for assessing the overall state of scour protection, rather than focusing on individual spot deformations. However, it is important to note that coarser meshes may fail to detect the initial occurrence of local phenomena, such as winnowing – the loss of sediment through the scour protection (Wörman, 1989; De Sonnevile *et al.*, 2014b; Riezebos *et al.*, 2016, Schendel and Schlurmann, 2019). This morphological process can trigger a local failure that could lead to progressive loss of structural integrity, even if the global volume of the protection is not significantly affected.

A critical review of the spatial scale reveals the limitations of standard failure criteria, as the sub-areas used in the adapted overlapping-circle method account for only a portion of the total scour protection area (Table 35). This disparity prompts a fundamental question: Can the structural failure of a scour protection system be reliably inferred solely from highly localised damage affecting a residual portion of the overall domain, or should it be evaluated from both global and local perspectives? The statistical evidence suggests that considering only local deformations may be methodologically limited, but the possibility of missing local failure mechanisms cannot be ruled out. Therefore, a joint global-local analysis should be considered to avoid the shortcomings of either approach.

Table 35 – Quantification of the spatial scale of damage analysis against scour protection footprint (prototype). values).

A_{sub}	Value [m ²]	$A_{sub}/A_{protection}$ (%)
D_{n50}^2	3.42×10^{-2}	0.006
$4D_{n50}^2$	1.37×10^{-1}	0.022
$9D_{n50}^2$	3.07×10^{-2}	0.050
A_{pile_jacket}	1.23	0.201
$A_{protection}$	612.56	
D_{n50} [m]	0.185	

The distinction is clearly described by the statistical tendencies observed:

- **High Grid Ratios (Micro-Scale):** characterised by higher skewness, positive kurtosis, and $S_{3D,max} \gg [P_{90}-P_{99}]$, indicating that extreme damage may be highly localised, representing spot deformations rather than global failure.
- **Low Grid Ratios (Macro-Scale):** characterised by lower skewness, negative kurtosis, and $S_{3D,max} \approx [P_{95}-P_{99}]$, indicating a more distributed damage response relevant to the overall integrity of the protection.

Hence, while high-resolution analysis is crucial for understanding scour initiation and detecting local failure mechanisms, global failure criteria should better correspond with scales that represent the overall structural performance of the scour protection armour layer. This indicates that extremely severe damage may be highly localised, but failure should also be assessed globally.

While high-resolution meshes can help capture worst-case scenarios and identify potentially dangerous scour initiation zones, they are often too sensitive for assessing global structural integrity. At such fine scales, extreme damage values may be statistically rare and over-represent damage, potentially conflating spot deformations with the overall stability of the protection system, which is essential for establishing real-life decision-making criteria.

Instead, structural performance should also be evaluated at a spatial scale that corresponds to an acceptable level of material loss following a specific hazard event. This requires a shift in paradigm where the failure criterion is initially defined based on permissible surface or volumetric loss (*e.g.*, 1%, 2%, 5%), then the appropriate A_{sub} and $\eta_{S3D,grid}$ values for analysis are selected, and finally, the overlapping-circle method is applied. Larger sub-areas, although associated with lower grid ratios and smoother distribution, may offer a more accurate assessment of the overall system behaviour. By using statistically robust, percentile-based metrics, this approach complements stakeholder requirements for informed decision-making.

Far from compromising model validity, the use of looser meshes shifts the focus from resolving specific point deformations to assessing the system's overall integrity. For operational purposes, this approach may not only be acceptable but also beneficial, providing significant reductions in time and costs while requiring less computational effort. Therefore, fine-resolution mesh analysis should still be used as a complementary diagnostic tool to identify localised areas of vulnerability. Simultaneously, system-level performance is assessed using coarser, physically meaningful spatial scales aligned with established acceptable failure criteria.

6.4. SCOUR PROTECTION GLOBAL DAMAGE EVALUATION

Current design methodologies and failure assessments of scour protections rely on the $S_{3D,max}$ derived from fixed (De Vos *et al.*, 2012) or overlapping sub-areas (Fazeres-Ferradosa *et al.*, 2020). Although reliability-based approaches have been introduced by Fazeres-Ferradosa *et al.* (2018b, 2019a, 2019d, 2019e) and validated with field data (Chambel *et al.*, 2022), significant limitations still exist in the standard failure criteria. Specifically, as De Vos *et al.* (2012) define S_{3D} as a reduction in armour layer thickness proportional to $n_s \cdot D_{n50}$, the standard failure threshold of $S_{3D,failure}=1.0$ is strictly valid for single-layer protections, *i.e.*, $t_s=D_{n50}$. This raises concerns regarding the conservatism of thicker armour layers, which can inherently withstand larger damage magnitudes without failure.

6.4.1. SPATIAL OR VOLUMETRIC-BASED APPROACH (GLOBAL SCOUR)

Furthermore, as shown in the previous statistical analysis, the overlapping method is highly sensitive to mesh resolution (grid ratio), which may detect point deformations rather than provide a more comprehensive view of the protection's structural instability. To evaluate the overall structural condition of scour protections, an alternative spatial or volumetric-based framework is suggested when using the overlapping method.:

- **1st stage:** define an acceptable spatial/volume loss ($A_L\%$ or $V_L\%$) of armour layer material.
- **2nd stage:** determine $A_{sub}=A_{protection} \times 1\%$, $\eta_{S3D,grid}$, and define $S_{3D,failure}=n_s$.
- **3rd stage:** run the overlapping-circle method.

being $A_{protection}$ the total surface area of the scour protection.

If any single sub-area produces a single $S_{3D,failure}$ value, the protection is considered a failure because the sub-area was intentionally scaled to precisely detect exactly where a certain percentage of the total volume (V_T) was completely eroded. The filter layer is fully exposed ($V_e=V_T \times V_L\%=A_{sub} \times S_{3D,failure}$), thus complying with the protection's overall structural requirements.

As a proof of concept, two $V_L\%$ values (0.5% and 1.0%) were selected to demonstrate this approach using the results from the area near pile D in the J_WR_14 test, which is considered close to failure. Figure 75 shows the results and comparison of a scale analysis derived for different $A_{\text{protection}}$, using two selected $V_L\%$. When comparing the spatial/volumetric-based scale results with material-based resolutions, a significant contrast is evident. For the high-resolution meshes, $S_{3D,max}$ ranges from 6.14 to 4.54, which should indicate failure, filter exposure, or severe damage.

Conversely, when A_{sub} was adjusted to reflect volumetric losses of 0.5% and 1%, the damage number decreased noticeably to 3.3-3.6. At these scales, $S_{3D,max}$ almost perfectly aligns with the upper-bound percentiles, indicating that grid choice affects filtering out some scattering. Additionally, visual inspections of the physical model showed no visible filter exposure (Figure 76), and the scour protection seemed to have maintained its overall integrity, which better supports the volumetric loss adjustment results and indicates a quite dynamic profile. This discrepancy suggests that high damage numbers at the initial resolutions may have resulted from point deformations or local stone reorientations rather than structural failure.

It is important to note that for the specific protection geometry, the value $V_L\%=1\%$ represented the practical upper limit for discretisation. Since A_{sub} depends on the total protection area, rather than an arrangement of armour layer units, increasing $V_L\%$ in this specific case above 1% would result in a sub-area too large to fit consistently within the protection boundaries without missing sub-area elements, *i.e.*, without losing data points. Therefore, the 0.5%-1% range offers a balance between robust statistical damage characterisation and geometric feasibility.

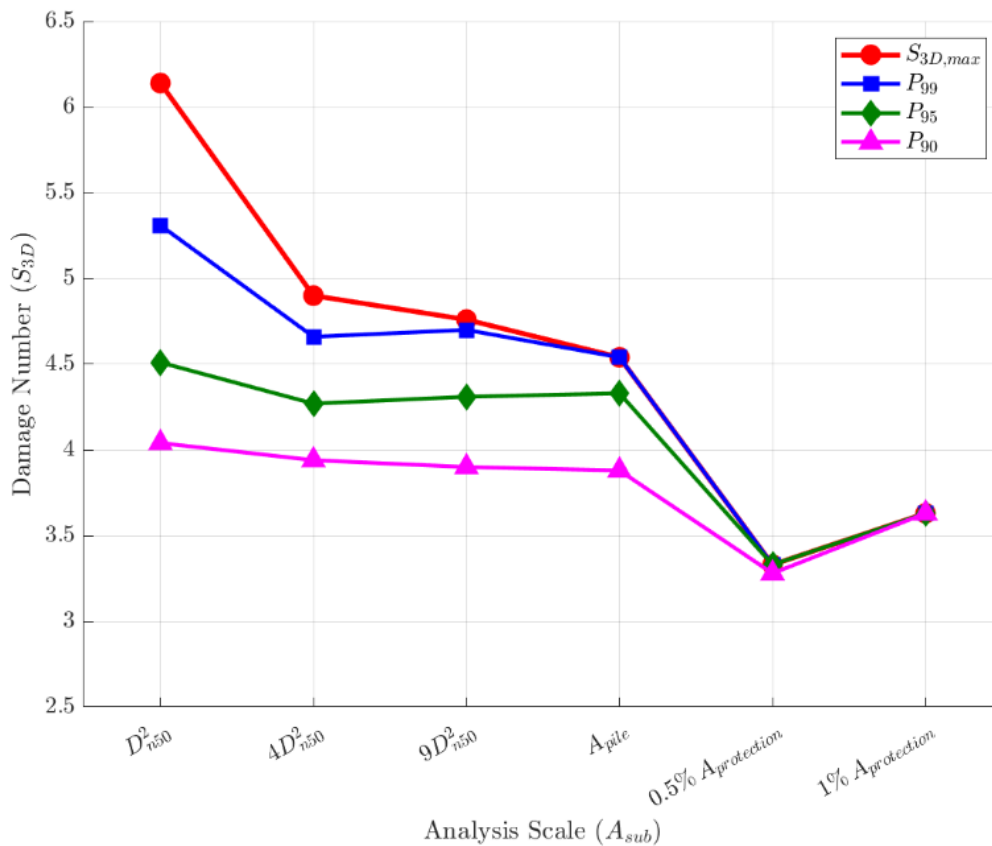


Figure 75 – Evolution of damage vs. mesh resolution: J_WR_14 test (pile D).



Figure 76 – Pile D after 3000 waves (J_WR_14 test).

6.5. SCOUR PROTECTION LOCAL DAMAGE EVALUATION

While the proposed spatial/volumetric framework evaluates the overall stability of protection, the four initial mesh resolutions remain essential tools for examining local phenomena. The fine-scale analysis can accurately measure scour in critical areas near the piles, aiding in identifying potential worst-case scenarios and locations that could serve as indicators of failure. Although it is understood that scour also requires this level of precision, as shown, the chosen grid ratio can inherently overstate the damage number. Therefore, the procedure outlined in sub-chapter 6.2.3 was applied using the dataset from the statistical analysis to preserve the diagnostic value of using both high- and low-resolution meshes.

6.5.1. FAILURE THRESHOLD ESTIMATION

The initial step involved ranking the pile areas based on the $S_{3D,max}$ and visual assessment (Table 36). Using this ranking system, the failure limit estimates (Step 2) were calculated as the average for the “Dynamic (Close to failure)” classification. Data points from dynamic areas near failure were used to establish a threshold representing this near-critical state, serving as a proxy for the actual threshold.

Step 3 focused on determining the correction factor to account for minor deviations from the theoretical target. The C_f value was obtained for the reference resolution and then applied to the results for all other grid resolutions (leading to Step 4). Table 37 summarises the results from Steps 2 through 4 and shows that:

- For the reference resolution ($A_{sub}=4D_{n50}^2$), the experimental mean damage number for the near failure condition was set at $S_{3D,FTE}=4.73$. To align this baseline with the reference failure limit (assumed to be $S_{3D,failure}=5.0$ for this setup), Step 3 yielded a C_f of 0.945.
- For the highest mesh resolution ($A_{sub}=D_{n50}^2$), an initial $S_{3D,FTE}=5.87$ was estimated. After applying the C_f , the adjusted failure limit is about $S_{3D,failure}\approx 6.21$, roughly a 24% increase over the reference limit. This indicates that when using the overlapping method, the threshold should be adjusted to account for mesh overestimation.

- For the lowest mesh resolution ($A_{sub}=A_{pile_jacket}$), an initial $S_{3D,FTE}=4.23$ was estimated. After correction, the failure limit increases to $S_{3D,failure}=4.48$, about 10% lower than the reference failure limit, reflecting the attenuation of peak damage values. Thus, the threshold should be adjusted to account for mesh underestimation.

The calibration values obtained are preliminary and will need refinement and validation with a more diverse set of experiments.

Table 36 – $S_{3D,max}$ vs. scour protection behaviour classification.

Structure	Test	Pile	D_{n50}^2	$4D_{n50}^2$	$9D_{n50}^2$	A_{pile_jacket}	Classification
Jacket	J_WC_7	A	1.93	1.29	1.21	0.90	Static
		B	2.05	1.26	0.98	0.48	
		C	1.24	0.85	0.42	0.07	
		D	2.04	1.72	1.30	0.95	
	J_WC_11	A	1.91	1.51	1.18	0.82	
		B	1.62	1.14	1.16	0.45	
		C	1.78	1.21	1.09	0.57	
		D	2.62	1.98	1.45	0.23	
	J_WR_14	A	2.81	2.17	1.79	1.17	Static (Close to Dynamic)
	J_WC_15.5	A	3.34	2.50	2.65	1.46	
		B	2.86	2.05	1.88	1.31	
		D	3.02	2.59	2.10	0.94	
	J_WI_14	A	4.35	3.39	3.07	2.84	Dynamic
		B	5.14	3.96	3.88	3.21	
		C	5.00	3.31	3.31	2.82	
		D	3.86	3.21	2.61	1.96	
	J_WR_14	B	3.65	3.37	2.76	2.52	
	J_WR_14	C	5.46	4.57	4.42	3.92	Dynamic (Close to Failure)
		D	6.14	4.90	4.76	4.54	
	J_WC_15.5	C	6.01	4.71	4.50	4.24	

Table 37 – Procedure to determine $S_{3D,failure}$ for different A_{sub} .

Classification: Dynamic (Close to Failure)		
A_{sub}	$S_{3D,max}$	Threshold Limit
D_{n50}^2	Max Value	6.14
	Min Value	5.46
	Mean Value	5.87
	$S_{3D,FTE}=5.87$	$S_{3D,failure}=6.21$
$4D_{n50}^2$	Max Value	4.90
	Min Value	4.57
	Mean Value	4.73
	$S_{3D,FTE}=4.73$	$S_{3D,failure}=5.00$
$9D_{n50}^2$	Max Value	4.76
	Min Value	4.42
	Mean Value	4.56
	$S_{3D,FTE}=4.56$	$S_{3D,failure}=4.82$
A_{pile_jacket}	Max Value	4.54
	Min Value	3.92
	Mean Value	4.23
	$S_{3D,FTE}=4.23$	$S_{3D,failure}=4.48$

6.5.2. STATIC THRESHOLD ESTIMATION

The estimation of the static limit focused on the subset “Static (Close to Dynamic)”. Table 38 displays the data values related to $S_{3D,static}$, while Table 39 shows the λ_{static} results obtained at various mesh resolutions. For the reference resolution ($A_{sub}=4D_{n50}^2$), the average static threshold was set to 2.33, serving as a benchmark for evaluating how grid resolution influences the perception of static behaviour. Since no reference static limit was available, no C_f was applied to any of the metrics. For each resolution, λ_{static} was calculated as the ratio of $S_{3D,static}$ to the corrected $S_{3D,failure}$.

Table 38 – Procedure to determine $S_{3D,static}$ for different A_{sub} .

Classification: Static (Close to Dynamic)		
A_{sub}	$S_{3D,max}$	
D_{n50}^2	Max Value	3.34
	Min Value	2.81
	Mean Value	3.01
	$S_{3D,static}$	3.01
$4D_{n50}^2$	Max Value	2.05
	Min Value	2.59
	Mean Value	2.33
	$S_{3D,static}$	2.33
$9D_{n50}^2$	Max Value	1.79
	Min Value	2.65
	Mean Value	2.11
	$S_{3D,static}$	2.11
A_{pile_jacket}	Max Value	0.94
	Min Value	1.46
	Mean Value	1.22
	$S_{3D,static}$	1.22

Table 39 – λ_{static} values for each respective A_{sub} .

Classification: Static (Close to Dynamic)	
A_{sub}	λ_{static}
D_{n50}^2	0.48
$4D_{n50}^2$	0.47
$9D_{n50}^2$	0.44
A_{pile_jacket}	0.27

This formulation normalises the static limit relative to the failure limit, ensuring that λ_{static} represents a fraction of the failure criteria at any given resolution.

- At the highest mesh resolution ($A_{sub}=D_{n50}^2$), $S_{3D,static}$ increased to 3.01, indicating that a higher threshold is needed to prevent misclassifying stable elements as dynamic, due to the mesh's high sensitivity to point deformations. Although $\lambda_{static}=0.48$ appears high compared to the failure threshold, a wider margin for the dynamic zone was observed, compensating for the capture of point deformations, which require a higher normalised threshold.

- Conversely, for $A_{sub}=A_{pile_jacket}$, the static damage number limit decreased to 1.22, effectively filtering out outliers and extreme values, providing a value that better reflects the limited mobility of an armour layer made of five layers of riprap material. The λ_{static} drops to 0.27, confirming that spatial averaging effectively filters out high local variations. At this resolution, the static level is significantly below the failure limit, reinforcing the expected behaviour in a motionless state.
- When analysing the complete set of λ_{static} values, three out of four resolutions yielded consistent values, ranging between 0.44 and 0.48. These results suggest that, at a local scale, the transition from static to dynamic behaviour occurs roughly around 0.45 of the failure thresholds. For the A_{pile_jacket} sub-area, the ratio drops to 0.27. This decrease may result from using a larger analysis sub-area, which captures not only localised erosion peaks but also significant sediment accretion zones.
- The decrease in λ_{static} may indicate that the A_{pile_jacket} resolution is in a transition phase where it filters out point deformations and begins to resemble a global analysis rather than relying on the finer mesh's local survey capabilities.

The values presented should be considered preliminary and require further validation with a broader experimental dataset.

6.5.3. PROOF-OF-CONCEPT

After estimating the static and failure thresholds for the four resolution meshes, these limits were compared with the $S_{3D,max}$ values from each test. This comparison aimed to verify whether the damage classification assigned to each test remained consistent across all resolutions when using the respective thresholds for each grid.

Table 40 shows that the static tests (J_WC_7 and J_WC_11) consistently report maximum damage numbers below the static threshold across all resolutions, effectively categorising them as static, regardless of the grid ratio used. Conversely, the remaining tests return values that exceed the static limit but stay below the failure threshold, except for the J_WR_14 test, which, at the coarser resolution, triggers a failure event by exceeding the S_{3D} .

Regarding the spatial location of the $S_{3D,max}$ value, Table 40 provides important insights. For the tests surpassing the static threshold (J_WC_15.5, J_WI_14, and J_WR_14), the peak damage location remains in the same pile area across all resolutions. As reported by Zhang *et al.* (2014), these high damage tests were associated with higher wave heights and longer peak wave periods. In contrast, static tests show some instability, particularly with the most impacted pile. For the J_WC_7 test, the $S_{3D,max}$ shifts from pile B in the finer mesh to pile D in the other meshes. For the J_WC_11 test, the opposite occurs: the $S_{3D,max}$ shifts from pile A in the lowest-resolution mesh to pile D in the higher resolutions. This variation in low-damage scenarios may suggest that, for static configurations in which the armour layer unit movement is residual when the armour layer material moves slightly, the maximum damage value is influenced by minor reorientations.

It is crucial to emphasise that the analysis and results presented in this sub-chapter act as a proof of concept for the calibration procedure proposed in sub-chapter 6.2.3, using the limited dataset currently available. To refine and validate this procedure, comprehensive experimental testing is necessary:

- Establish how sensible results can be to a wider range of hydrodynamic conditions.

- To assess how different combinations of waves and/or current conditions can dictate damage patterns and establish the most prone damage locations.
- To verify whether the transition between static, dynamic, and failure behavioural stages, at both local and global, consistently occur at these specific fractions of the failure limit, or if they may vary significantly under broader hydrodynamic conditions

Furthermore, future research should prioritise redundancy tests to ensure data reliability and to isolate whether the observed variations were systematic or stochastic.

Table 40 – Comparison of $S_{3D,max}$ location with threshold limits obtained.

$S_{3D,max}$ vs Thresholds					
A_{sub}	Damage Classification (Overall)	D_{n50}^2	$4D_{n50}^2$	$9D_{n50}^2$	A_{pile_jacket}
$S_{3D,static}$		3.01	2.33	2.11	1.22
$S_{3D,failure}$		6.21	5.00	4.82	4.48
J_WC_7	Static	2.05 (Pile B)	1.72 (Pile D)	1.30 (Pile D)	0.95 (Pile D)
J_WC_11	Static	2.62 (Pile D)	1.98 (Pile D)	1.45 (Pile D)	0.87 (Pile A)
J_WC_15.5	Dynamic (Close to Failure)	5.66 (Pile C)	4.71 (Pile C)	4.50 (Pile C)	4.24 (Pile C)
J_WI_14	Dynamic	5.14 (Pile B)	3.96 (Pile B)	3.88 (Pile B)	3.21 (Pile B)
J_WR_14	Dynamic (Close to Failure)	6.14 (Pile D)	4.90 (Pile D)	4.76 (Pile D)	4.54 (Pile D)

6.6. CONCLUSIONS

This research presents a novel row-by-row overlapping method that extends the original concept (Fazeres-Ferradosa *et al.*, 2020) to manage complex foundations and non-standard scour protection geometries. The effect of mesh resolutions on damage quantification and distribution was examined by comparing four different grid ratios and sub-areas. The analysis provides a way to modify static, dynamic, and failure threshold limits based on the grid ratio used in bathymetric profile analysis. Through detailed statistical analysis, the link between the mesh resolution and damage was identified. The following points summarise the key contributions of this chapter:

- **Successful modification and application of the overlapping-circle method:** Although projected and developed to be applied to a multitude of rubble-mound marine structures, the study cases reported by Fazeres-Ferradosa *et al.* (2020) and Chambel *et al.* (2023b, 2025) involved only monopiles and circular scour protections. This research successfully modified it to fit a 4-leg jacket safeguarded by a square protection, proving that the method can be reliably applied to a variety of setups with non-standard structural features.
- **Mesh resolution vs damage number quantification:** High-resolution mesh ($A_{sub}=D_{n50}^2$) produced the highest $S_{3D,max}$, driven by positive skewness and excess kurtosis, indicating that the values may reflect extreme local deformations rather than overall failure. Conversely, coarser resolutions ($A_{sub}=A_{pile_jacket}$) tended to smooth out data scatter, resulting in distributions

where upper-percentile values approach the maximum. This confirms that high-resolution grids are sensitive to local unit deformations, while coarser resolutions may better distinguish between minor deformations and critical structural failures.

- **Application of framework to assess global spatial-volumetric loss:** To better address the difference between local and overall scour damage, a new framework was proposed. Instead of focusing on residual exposure of the filter layer, the method evaluates the spatial and volumetric loss of armour layer material. When applied to experimental data, this approach showed that protections previously considered near failure under the reference criteria ($A_{sub}=4D_{n50}^2$) displayed higher levels of structural integrity. Specifically, using the volumetric approach with $V_{L\%}=1\%$, $S_{3D,max}$ decreased from 6.14 to 3.6 (for the J_WR_14 test), bringing the maximum value closer to the upper percentiles and filtering out localised deformations, resulting in damage estimates that better match visual observations. This suggests that defining failure based on a larger permissible volume of material loss may be a more meaningful and practical criterion for large-scale monitoring and decision-making.
- **Proposal of a new calibration protocol to adjust static/failure thresholds to complex foundations:** Although high-resolution meshes (smaller circles) tend to overestimate damage, they remain valuable for detailed local analysis, accurately capturing scour near piles and aiding in identifying potential failure precursors and critical areas. Consequently, a calibration protocol was developed to adjust the static and failure thresholds based on mesh resolution. Based on the results, a correction factor was determined and applied to the initial failure threshold estimates ($S_{3D,FTE}$), ensuring consistent diagnostics across different mesh sizes and preventing false alarms. The final failure thresholds ($S_{3D,failure}$) were adjusted approximately by +24% ($A_{sub}=D_{n50}^2$) and by -10% ($A_{sub}=A_{pile_jacket}$) compared to the reference resolution ($A_{sub}=4D_{n50}^2$). For the static threshold, the protocol introduces a static ratio (λ_{static}), allowing $S_{3D,static}$ to be expressed as a percentage of $S_{3D,failure}$ for each resolution. This ratio was reduced from 0.48 ($A_{sub}=D_{n50}^2$) to 0.27 ($A_{sub}=A_{pile_jacket}$), illustrating how coarser resolutions filter data.

Using these calibrated thresholds, the study provides a protocol for reliably evaluating scour protection performance independent of mesh resolution. It should be noted that the proposed quantitative thresholds are preliminary and serve as a proof of concept; further testing is required to establish definitive values. The effective application of a dual-scale assessment method for local and global damage, using the overlapping-circle technique for scour protection, offers a post-processing tool for accurate evaluations, supporting maintenance planning and survey analysis. These assessments, supported by detailed statistical analysis, enable precise failure detection based on local deformations.

7. Optimised Protections for a Large-Scale Offshore Hybrid Structure

7.1. INTRODUCTION

The large-scale experimental study described in Chapter 3 was idealised to evaluate the feasibility and performance of two different scour protection systems under realistic wave-hydrodynamic conditions and WEC-induced motions, applicable to a standard and hybrid monopile structure. The performance of both protection systems was analysed and compared. The work advances the state of the art by presenting a benchmark large-scale physical model test of a protected hybrid structure. By coupling an OSWEC to the offshore structure, this work quantifies how the device's oscillatory motion influences turbulence and hydrodynamics, thereby modifying the mechanisms of scour protection failure. Additionally, a novel pair of equations is proposed to address the need for an approach that reduces disparities between predictive and measured results on protected standard and hybrid structures, thereby mitigating misrepresentations arising from the amplification of the main flow patterns that drive the scouring process.

Large-scale physical model testing requires an understanding of possible scale effects, as recent literature highlights that small-scale models often fail to capture critical hydrodynamic mechanisms, leading to inaccuracies of scour depth, damage, and location (Schendel *et al.*, 2014; Chen and Li, 2018; Arboleda-Chavez *et al.*, 2019; Wu *et al.*, 2020, 2022; Chen *et al.*, 2022; Gong *et al.*, 2023, 2025; Jalloul *et al.*, 2026). In the context of unprotected monopiles, large-scale experiments have established that scour mechanisms are susceptible to the KC number and to the relative monopile size (D/L). Chen and Li (2018), Chen *et al.* (2022), and Gong *et al.* (2023) confirm a distinct transition in the location of maximum scour: at low KC numbers, generally below 4, scour is dominated by streamline contraction on the lateral sides, whereas at higher KC numbers, generally above 8, the scour shifts to the downstream region. However, Gong *et al.* (2025) recently identified that this behaviour is not uniform. For large monopiles ($D/L > 0.04$), scour remains concentrated on the sides regardless of wave parameters, also contradicting some observations from small-scale testing. Moreover, Chen *et al.* (2022) and Gong *et al.* (2023, 2025) observed that existing prediction models tend to underestimate scour depths at low KC numbers due to scale effects. Jalloul *et al.* (2026) demonstrated that the Re_D significantly impacts the timescale of scour development, a factor previously neglected in standard design formulae.

Regarding large-scale experimental studies of scour protection systems, the number of datasets is limited. Nevertheless, research has consistently demonstrated that current design standards (De Vos *et al.*, 2011, 2012) are often overly conservative compared with large-scale results. Schendel *et al.* (2014) tested wide-graded materials as an alternative for static protection for a large-scale monopile. It was concluded that wide-graded protections can form a self-stabilising armour layer that withstands higher

bed loads, a behaviour that the traditional static design approach failed to capture. Moreover, it concluded that the predicted values based on DNV (2010) design standards and De Vos *et al.* (2011) equations yielded overly conservative estimates compared with the measured results. Recently, DNV (2022) introduced updated guidelines for the design of rock scour protections around monopiles. Nevertheless, it contains no references to hybrid structures or recommendations.

Arboleda-Chavez *et al.* (2019) and Wu *et al.* (2020) reported that $S_{3D,measured}$ was significantly lower than $S_{3D,predicted}$ using Equation (4). Overestimations by factors of 2 to 5 times were registered. Both authors point out that scale and model effects cause deviations, not the formula's over-conservatism. Therefore, Wu *et al.* (2022) quantify these scale effects by comparing three large and small-scale tests under similar hydrodynamic conditions, suggesting that small-scale models may yield higher damage rates due to exaggerated wake vortices on the lee side of the pile, which are absent in large-scale conditions.

A more detailed examination of the experimental results presented by Wu *et al.* (2022) indicates a more complex relationship between scale and damage than the general conclusion reported. In two comparisons, the damage levels and extent were lower or similar in the large-scale test than in its small-scale counterpart. It is important to note that no comparison with the predicted value is made, and that the small-scale results were reported as $S_{3D,mean}$ values with 95% confidence intervals, rather than $S_{3D,measured}$ values, which limits a direct one-to-one comparison. However, the author also acknowledges that using only two tests as a sample may limit the scope of comparison. For the final test comparison, two iterations of a small-scale test are compared against a single iteration of a large-scale test. One of the small-scale tests showed significantly higher damage rates, while the other again showed a similar value. Nonetheless, Wu *et al.* (2022) emphasise that despite identical hydrodynamic conditions, differences in armour layer gradation among the models may influence the results. Therefore, when using a similar test by Arboleda-Chavez *et al.* (2019) under the same conditions and gradation, the data again reveal that a single small-scale test yielded damage values comparable to those of the large-scale observations. In contrast, the other iteration showed more serious damage. This suggests that the 'conservatism' of small-scale models may not be absolute across all test conditions. Nonetheless, it is important to note that the De Vos *et al.* (2012) equation appears to inaccurately predict damage in both large- and small-scale models.

To assess some of the nuances and complexities reported in the literature, a large-scale physical model experiment, detailed in Chapter 3, was conducted to advance understanding of damage progression and the influence of a fully functional, late-stage WEC developed at OSU on scour-generating flow mechanisms around both a standard and a hybrid monopile. Conducted as part of the technical support received by the TEAMER program, this work advances the state of the art by presenting the first large-scale testing of a hybrid structure equipped with a functional WEC. The primary objective is to assess the behaviour of two distinct scour protection designs, optimised based on the performance results from the small-scale testing presented in Chapter 4, and to determine whether current design equations indeed fail to predict the S_{3D} , as emphasised in the previous chapters.

7.2. SCOUR PROTECTION DAMAGE ANALYSIS

The quantitative assessment of damage for the experimental research performed at the HWL-OSU followed the same protocol as in the previous chapters. The S_{3D} for each test was computed by applying the overlapping-circle method for a $A_{sub}=4D_{n50}^2$ and an overlapping distance of 50%. Table 41 summarises all measured conditions for the entire 3000-wave duration. Since an ADV was not only

available at the wave gauge locations but also at the structure, on top of the scour protection, it was possible to measure not only the incident orbital velocities but also the orbital velocities that occur in the vicinity of their foundation ($U_{m,foundation}$). This allowed for a more precise analysis of the effects of the hybrid structure on turbulence amplification. However, it is necessary to highlight that, although the hydrodynamic conditions are not directly comparable because they are not identical, the adjustments maintained the incident orbital velocities and KC number constant across all tests, ensuring hydrodynamic similarity in how waves interact with the model, including vortex shedding and flow patterns. It is also important to note that, although the absolute thickness value used across all tests was the same, the static protection comprised fewer layers ($n_s=1.56$) than the dynamic protection ($n_s=6.25$).

Table 41 – Experimental measured conditions for large-scale tests (model values).

Test	No. of Waves	H_{mo} [m]	T_p [s]	U_m [m/s]	KC	$U_{m,foundation}$ [m/s]	$KC_{foundation}$	S_{3D} (Predicted)	S_{3D} (Measured)
MS	3000	0.371	3.151	0.405	5.80	0.446	6.39	0.46	0.59
HFS	3000	0.502	3.151	0.413	5.92	0.579	8.29	0.40	1.13
HMS	3000	0.512	3.151	0.411	5.89	0.567	8.12	0.40	0.90
MD	3000	0.365	3.151	0.403	5.77	0.452	6.47	7.36	4.59
HFD	3000	0.501	3.151	0.414	5.93	0.565	8.09	6.51	5.48
HMD	3000	0.508	3.151	0.418	5.99	0.566	8.11	6.73	6.12

7.2.1. STATIC PROTECTION

This visual assessment of the monopile's static protection (Figure 77) confirms the minor deformations detected by the measured $S_{3D}=0.59$ (Table 41, Figure 79). With the integration of the OSWEC, orbital velocities increased, leading to greater damage. For the HFS tests (Figure 80), the most affected static protection, S_{3D} occurred from 0.59 to 1.13, a 91% increase relative to the monopile. This confirms that in survival modes (locked flaps), the WEC acts as a substantial bluff body near the seabed, accelerating flow and intensifying turbulence acting on the protection. When the flaps were operational, the damage number decreased to 0.90 (Figure 78, Figure 81). While this consists of an improvement over the fixed case, showing the flaps' potential to absorb some of the hydrodynamic condition's energy, it still represents a 52% increase compared to the MS case. When comparing the measured S_{3D} to the predicted value from Equation (4), all damage number measurements were significantly higher, particularly for the hybrid structure, demonstrating that the De Vos *et al.* (2012) formulation underestimates deformations in static protections and fails to capture the WEC's hydrodynamic influence. As in the small-scale tests, coupling a converter to a monopile foundation increased damage to almost twice the level observed for the monopile. On the other hand, despite the tested conditions representing a more severe case, the protection endures all 3000 waves, whereas in the small-scale testing, it failed after 1000 waves. This shows a good agreement with the assessment by Wu *et al.* (2020), which suggests that large-scale scour protection can withstand higher bed loads than expected and that scour deformations remain smaller than predicted by standard formulas, highlighting the impact of scale and model effects.

When focusing on the observed damage patterns, the damage recorded in the MS test (Figure 79) was overall highly uniform. The protection shows a distribution of minor displacements, with no distinct focal points of deep erosion, suggesting that the bed shear stresses were evenly distributed and generally insufficient to initiate significant stone mobility. For the hybrid structures, tests HFS and HMS reveal an almost symmetric damage ring in the immediate vicinity of the structure, which is more pronounced for the HFS test. This radial sorting indicates a strong horseshoe vortex system and accelerated near-bed velocities, driven by the converter's blockage. While the static protection system proved resilient enough to prevent failure, the 50-90% increase in damage for the hybrid configurations underscores the need to bolster the protection thickness in the vicinity of the structure. However, the use of a more resilient material and the extended armour layer to cover the full spatial extent of the OSWEC seem to be reliable optimisations, as indicated by the results of the small-scale testing.



Figure 77 – Static protection after 3000 waves (MS test).

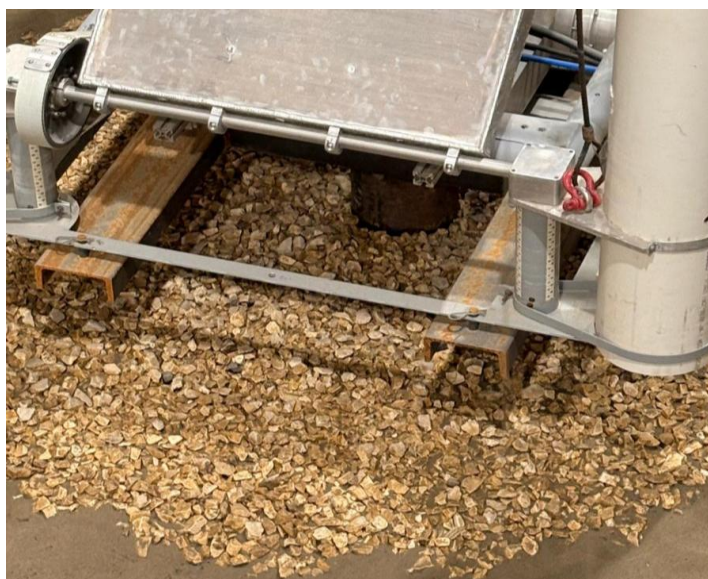
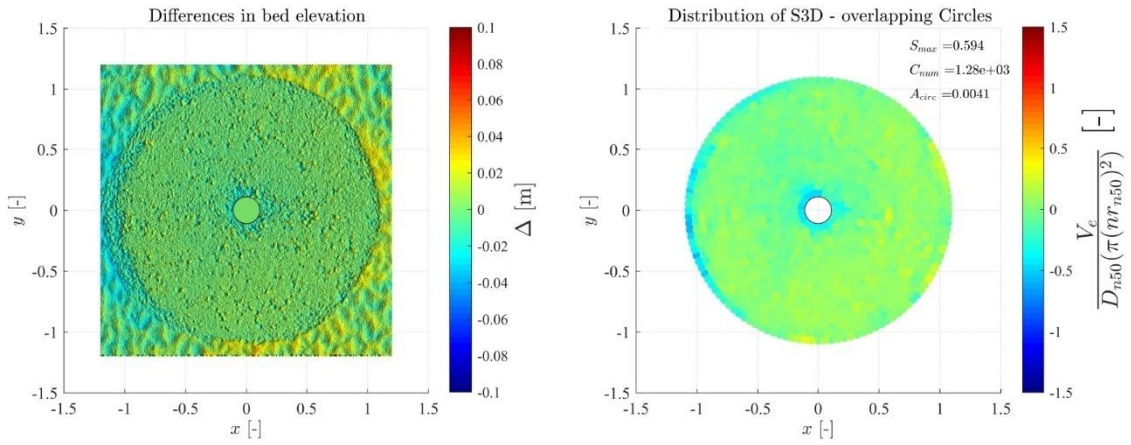
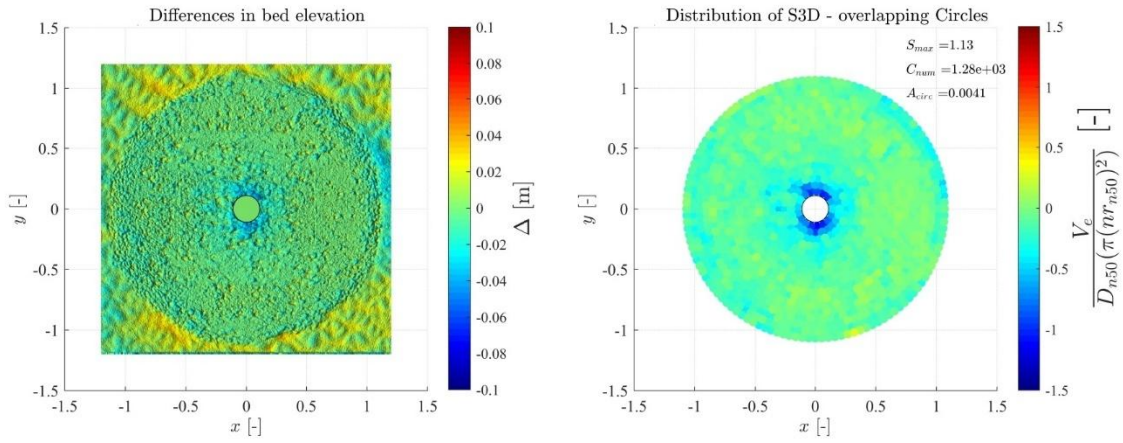
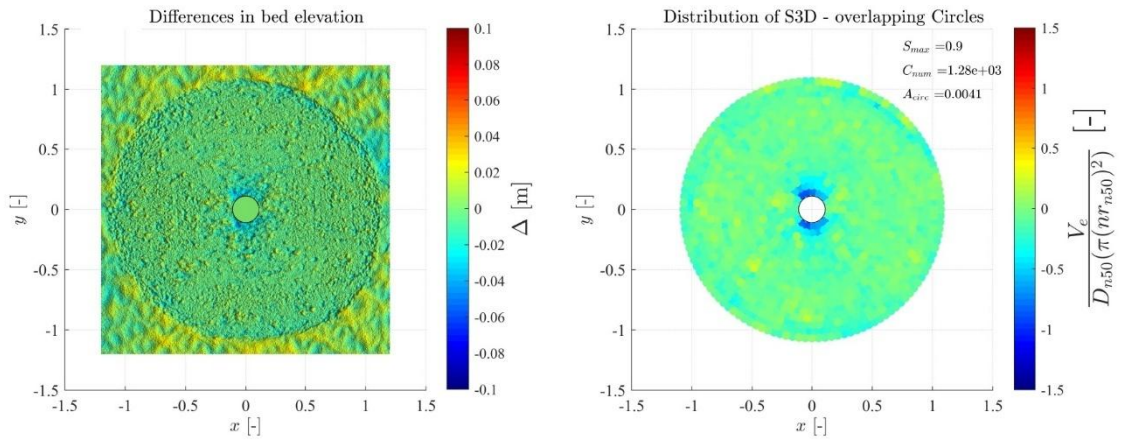


Figure 78 – Static protection after 3000 waves (HMS test).


 Figure 79 – MS test result: DTM (left) and S_{3D} distribution (right).

 Figure 80 – HFS test result: DTM (left) and S_{3D} distribution (right).

 Figure 81 – HMS test result: DTM (left) and S_{3D} distribution (right).

7.2.2. DYNAMIC PROTECTION

The performance of dynamic scour protection, as expected, showed more damage and higher S_{3D} values than in the static protection tests (Table 41). For the MD test, despite a dynamically stable visual assessment after 3000 waves (Figure 82), $S_{3D}=4.59$ indicates significant deformation of the armour layer (Figure 84). As expected, the dynamic protection was more sensitive to the enhanced turbulence generated by the converter, resulting in a severe escalation in damage (Table 41). With the flaps fixed (Figure 85), the damage number increased to 5.48, representing a 19% increase relative to the monopile test. Unlike static protection, which appears to benefit marginally from the "compliance" of moving flaps, the smaller material comprising dynamic protection seems more susceptible to the amplified orbital velocities and wake turbulence induced by the paddle motion, leading to rapid, cumulative material extraction. The HMD test showed the highest damage (Figure 83), peaking at 6.12 (Figure 86) and approaching the $n^s=6.25$ limit for protection failure, representing a 33% increase over the monopile baseline.

When comparing the measured S_{3D} to the predicted value (Table 41), overall, Equation (4) still fails to accurately predict damage, but this time it overestimates it as reported by Arboleda-Chavez *et al.* (2019), Fazerres-Ferradosa *et al.* (2020), and Wu *et al.* (2020). For the monopile, the overestimation reaches almost 60%, which is still lower than the 2-5 amplifications reported by Wu *et al.* (2020). Nonetheless, it predicts that the MD test should have resulted in the highest damage and the HMD the lowest, which is contrary to the measured results and, once again, shows the equation's inability to capture the WEC's hydrodynamic influence.

Regarding the spatial distribution of damage, the damage patterns observed align with the reports by Chen and Li (2018), Chen *et al.* (2022), and Gong *et al.* (2023, 2025) for large-scale wave-only tests: deformation occurs on the lateral sides of the structure and with the increase of KC number (related to the increase on turbulence), it shifts to the downstream region of the pile. For the MD Test, the damage distribution is concentrated on both sides (Figure 84), with deposition on the back of the structure after 3000 waves. In the HFD setup, damage intensifies and spreads across the back half of the structure (Figure 85), with deeper penetration in the wake region. This could indicate that the converter's complex configuration and features generate strong lee-wake vortices that strip the smaller dynamic stones more effectively than standard monopile vortex shedding does. Moreover, a small upstream deformation spot was observed, likely due to downflow induced by the converter's complex structural features. As for the HMD test, it exhibited the highest damage number, with a pattern similar to that of the fixed configuration (Figure 86). Deep erosion lobes (Figure 83) significantly reduce the thickness of the protective layer. Not only were the damage areas deeper, but both the accretion and erosion of material on the upstream side of the structure may also suggest that the WEC's paddle movement kept the material in constant motion, driven by increased turbulence and enhanced flow mobility.

Although less intense, the damage patterns in the large-scale tests followed the trend observed in small-scale modelling, with paddle oscillation amplifying lee-wake and counter-rotating vortices. Notably, the protection withstood the full 3000-wave cycle under severe conditions, whereas the small-scale equivalent failed after 1000 waves. This corroborates the findings of Wu *et al.* (2020), who reported that large-scale protections exhibit greater stability than predicted. However, the reduced damage is likely also due to the structural response of the fully operational PTO system, which provides a more realistic energy-dissipation mechanism than the simplified spring systems used in the small-scale tests.

Overall, the results indicate that the Hybrid Monopile inherently introduces a higher risk profile than the standard monopile. While the updated design parameters (increased material size, scour protection

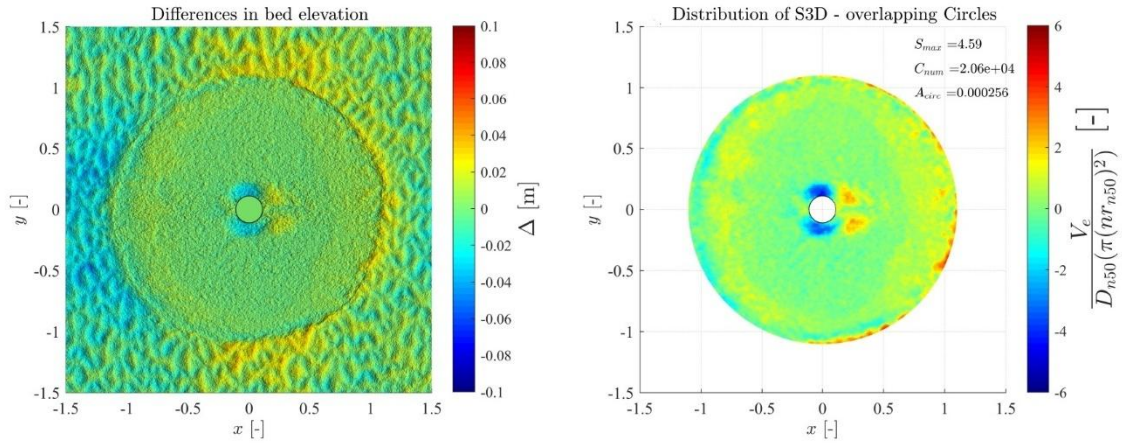
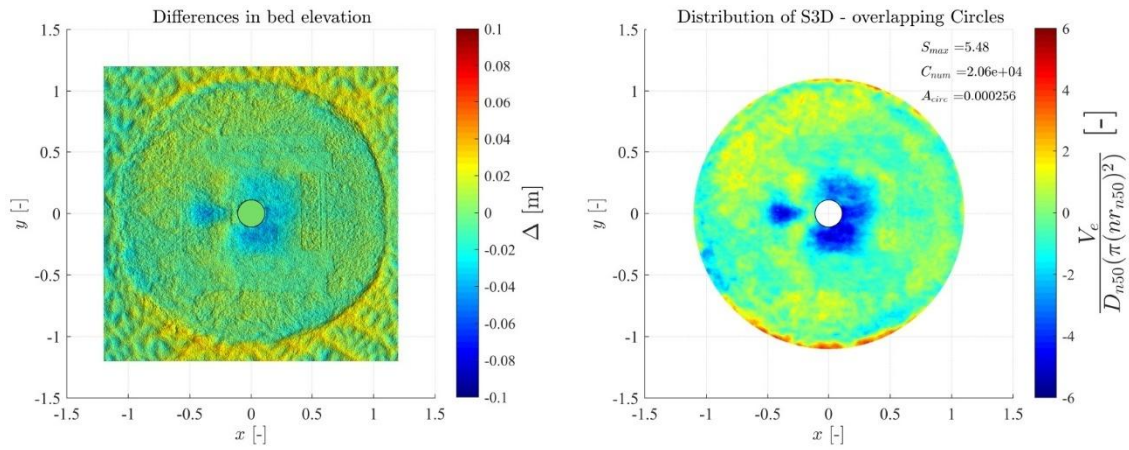
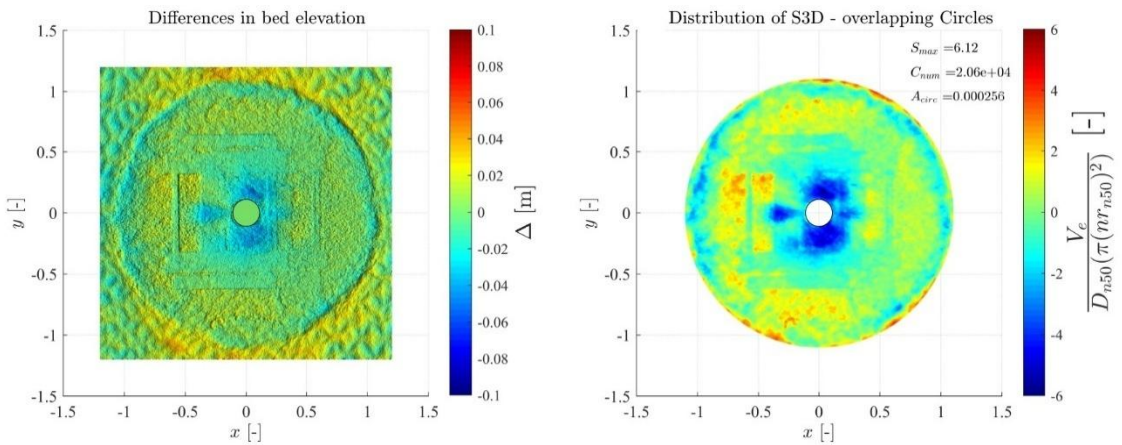
extent, and thickness) successfully prevented failure, the dynamic protection approached its stability limit. This underscores the need to upscale scour protection designs for hybrid applications to accommodate the amplified turbulence and load regimes specific to these multi-use structures.



Figure 82 – Dynamic protection deformation after 3000 waves (MD test).



Figure 83 – Dynamic protection deformation after 3000 waves (HMD test).


 Figure 84 – MD test result: DTM (left) and S_{3D} distribution (right).

 Figure 85 – HFD test result: DTM (left) and S_{3D} distribution (right).

 Figure 86 – HMD test result: DTM (left) and S_{3D} distribution (right).

7.2.3. S_{3D} VS GRID RATIO

As the grid ratio strongly influences the damage number determined by the overlapping-circle method, and considering the size of a large-scale protection, the grid ratio analysis selected only a few amount of A_{sub} values, including the monopile cross section (A_{pile}), that represents 1% of the foundation area, as suggested in the Chapter 6, and also an arrangement of multiple armour layer units $[n \times n]D_{n50}^2$. An additional A_{sub} was included to evaluate an area equivalent to 0.5% of the protection extension. However, due to the very small size of the dynamic protection material relative to the scour protection dimension, it was not possible to extract the S_{3D} value for $A_{sub}=D_{n50}^2$ because of the high computational requirements.

Since varying the grid ratio changes the number of elements analysed, it can significantly affect the maximum damage number (Figure 87). Higher grid ratios entail lower A_{sub} , more sub-areas, thus the scour pattern becomes closer to the DTM representation. However, it also increases the probability of obtaining more extreme values and outliers, which may represent a single spot deformation instead of capturing the overall state and capacity of the protection.

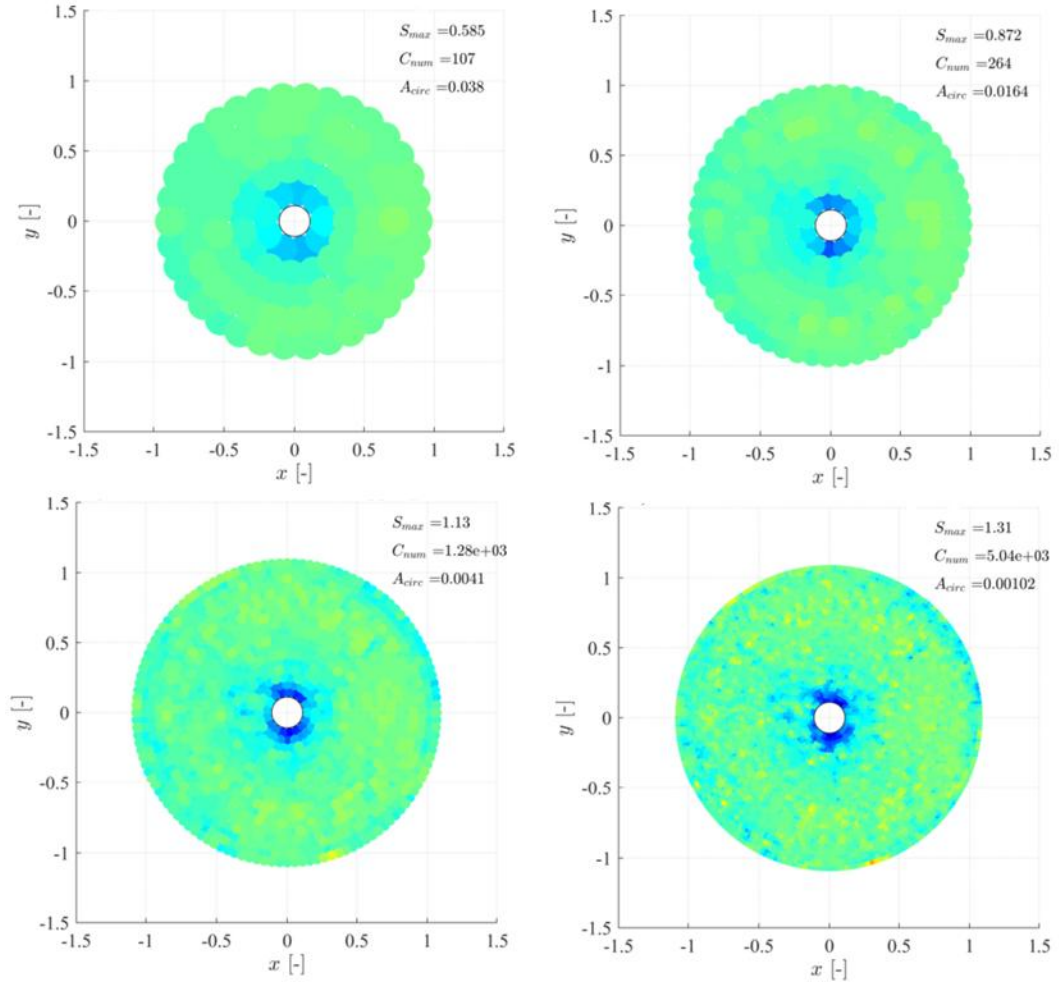


Figure 87 – Influence of the grid ratio on S_{3D} distribution for the HFS test: $A_{sub}=A_{pile}$, $\eta_{S3D,grid}=2.69 \times 10^{-2}/10$ (top left); $A_{sub}=16D_{n50}^2$, $\eta_{S3D,grid}=1/16$ (top right); $A_{sub}=4D_{n50}^2$, $\eta_{S3D,grid}=1/4$ (bottom left); $A_{sub}=D_{n50}^2$, $\eta_{S3D,grid}=1$ (bottom right).

The results for $S_{3D,max}$ vs $\eta_{S3D,grid}$ were plotted in Figure 88 (static protection tests) and Figure 89 (dynamic protection tests). Both plots show conclusions similar to those in Fazerer-Ferradosa *et al.* (2020), indicating a dependency and a positive correlation between the damage number and the grid ratio and/or the size of the selected subarea. Both show that different grid ratios yield entirely different results, potentially leading to different interpretations of scour protection behaviour. When analysing the plots, $S_{3D,max}$ curve shows an exponential decay form, increasing rapidly at first and then levelling off to become asymptotic, approaching the highest growth rate. For the static protection tests, the level-off seems to occur lately, around $\eta_{S3D,grid}=[1/4, 1/2]$ ($A_{sub}=[4, 2]D_{n50}^2$). For the dynamic protection tests, the stabilisation of $S_{3D,max}$ begins earlier, around $\eta_{S3D,grid}=1/25$ ($A_{sub}=25D_{n50}^2$). Although the static protection armour layer material is four times the size of the one used for the dynamic protection, thus being less susceptible to movement, these differences could be related to the fact that the number of layers “available” to be eroded is relatively lower for the static protection. Therefore, a single movement of a larger stone may induce higher variations for thigh overlapping meshes. Despite the increased damage, Figure 88 confirms that static protection tests remained below the theoretical Failure Limit, indicating that, while the hybrid structure induces higher stress, the designed static protection has sufficient capacity to withstand the amplification of flow patterns without catastrophic failure.

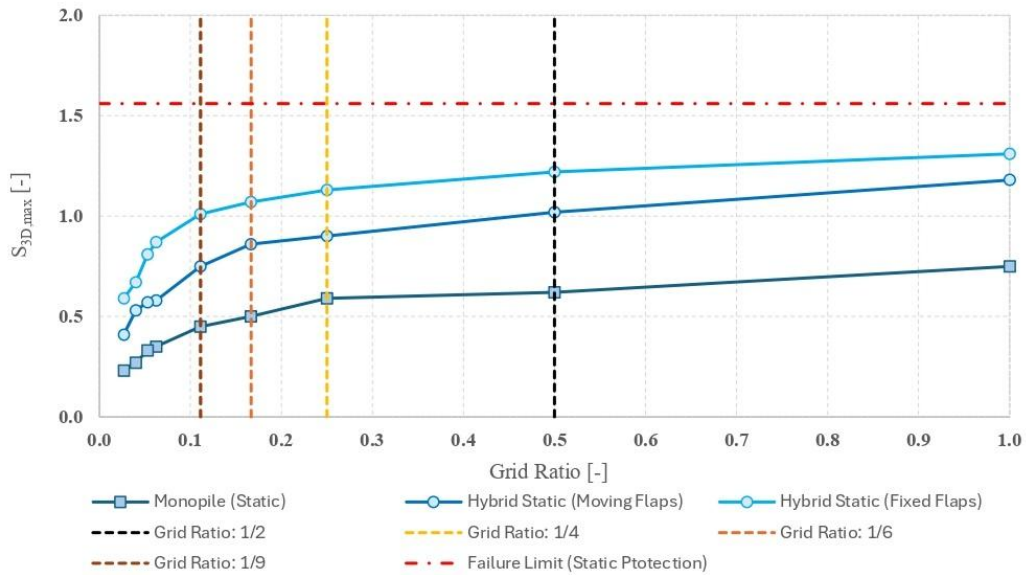


Figure 88 – Variation of the $S_{3D,max}$ with the $\eta_{S3D,grid}$: static protection tests.

As far as global damage is concerned, by analysing the lower grid ratios, which correspond to 0.5% to 1% of scour protection area, excepting the HFD and HMD tests, the measured $S_{3D,max}$ can be 2 times (MS, HFS, and HMS tests) to 4 times (MD test) lower. When assessing the visual damage to protections globally (e.g., Figure 77 and Figure 78), the static protection state appears more consistent with results from lower $\eta_{S3D,grid}$ than with those from higher $\eta_{S3D,grid}$. However, for the MD test, the visual assessment (Figure 82) indicates an underestimation of the scour protection deformation in the higher sub-areas of analysis. As for the HFD and HMD tests, both curves are flatter, indicating that the differences between the results for the higher and lower grid ratios decrease. This suggests that damage in hybrid structures is severe, widely distributed, and spatially symmetric over a large area. However, it is worth noting that

for the highest grid ratio used in the dynamic analysis ($A_{sub}=2D_{n50}^2$, $\eta_{S3D,grid}=1/2$), the HMD crossed the failure threshold, and the HFD is also dangerously close to it.

When reviewing Figure 83, it is possible to observe intense localised pockets of damage but no blatant failure or exposure of the seabed, highlighting the methodological danger of using tighter meshes. However, the $A_{sub}=A_{pile}$ and $A_{sub}=0.5\%A_{protection}$ slightly underestimate damage, despite still presenting a high S_{3D} value. In this case, the $\eta_{S3D,grid}$ starting at $1/25$, once again seems to capture a more accurate value relative to the detected damage. However, it is the $\eta_{S3D,grid}=[1/9, 1/4]$ interval that presents the most reliable representation of the real state of the scour protection. Compared to the small-scale tests, the damage number for the hybrid structure remained nearly unchanged regardless of the A_{sub} chosen, due to the excessive deformation observed. However, for the monopile foundation, results showed a stabilising effect between $\eta_{S3D,grid}=1/6$ ($A_{sub}=6D_{n50}^2$) and $\eta_{S3D,grid}=1/4$ ($A_{sub}=4D_{n50}^2$). The results of each experimental study indicate that $A_{sub}=4D_{n50}^2$ remains the most reasonable threshold for identifying local scour failure of the protection. In the end, the local amplification of the main scour drivers by the WEC seems to increase the need for high-resolution monitoring.

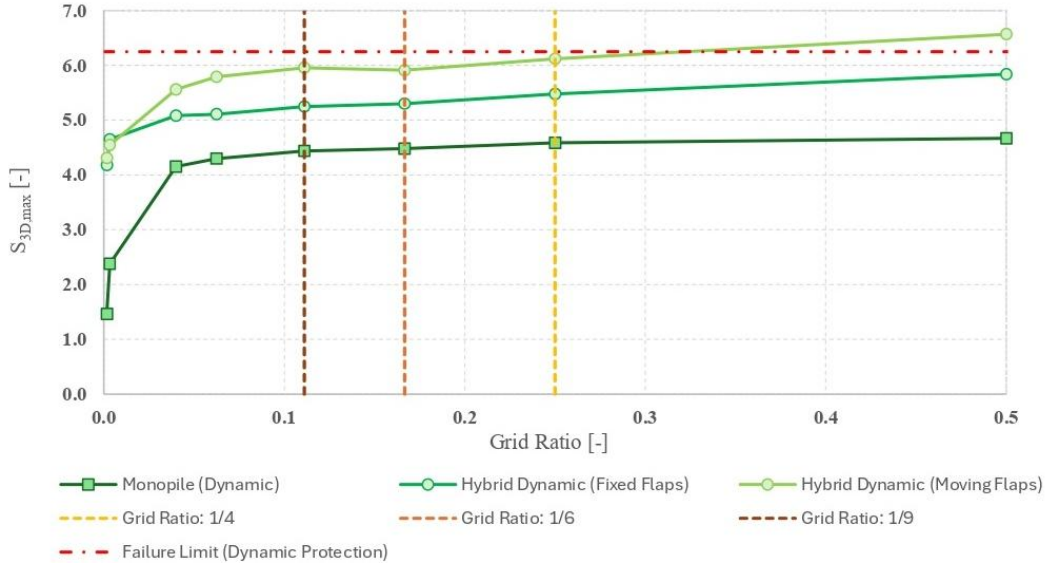


Figure 89 – Variation of the $S_{3D,max}$ with the $\eta_{S3D,grid}$: dynamic protection tests.

7.3. INFLUENCE ON FLOW MODIFICATIONS (INCIDENT/TRANSMITTED)

The following analysis characterises the impact of both structures on the modification of the imposed hydrodynamic conditions. By examining the orbital velocities recorded at the offshore (ADV1), vicinity (ADV2), structure (ADV3), and onshore (ADV4) locations (Figure 90), it was possible to quantify and provide critical insights into the flow modifications induced by the hybrid structure relative to a standard monopile.

As shown in Table 42 and Figure 91, the consistency of the generated hydrodynamic conditions is confirmed. The significant ($U_{m,s}$) and maximum orbital velocities ($U_{m,max}$) at ADV1 and ADV2 remained stable across all test series. Table 43 shows that the velocity ratio between ADV2 and ADV1, for the $U_{m,s}$ ratio ($\alpha_{U_{m,s}}$), remains practically unchanged (0.95–1.04). As for the $U_{m,max}$ ratio ($\alpha_{U_{m,max}}$), it also remains relatively close to 1 across most tests. This highlights that the structure's effects on the flow are

highly localised and do not significantly alter the flow field at the distance of ADV2. This consistency ensures that deviations observed at the structure (ADV3) can be attributed to the structure's geometry and characteristics, where the most critical hydrodynamic alterations occur.

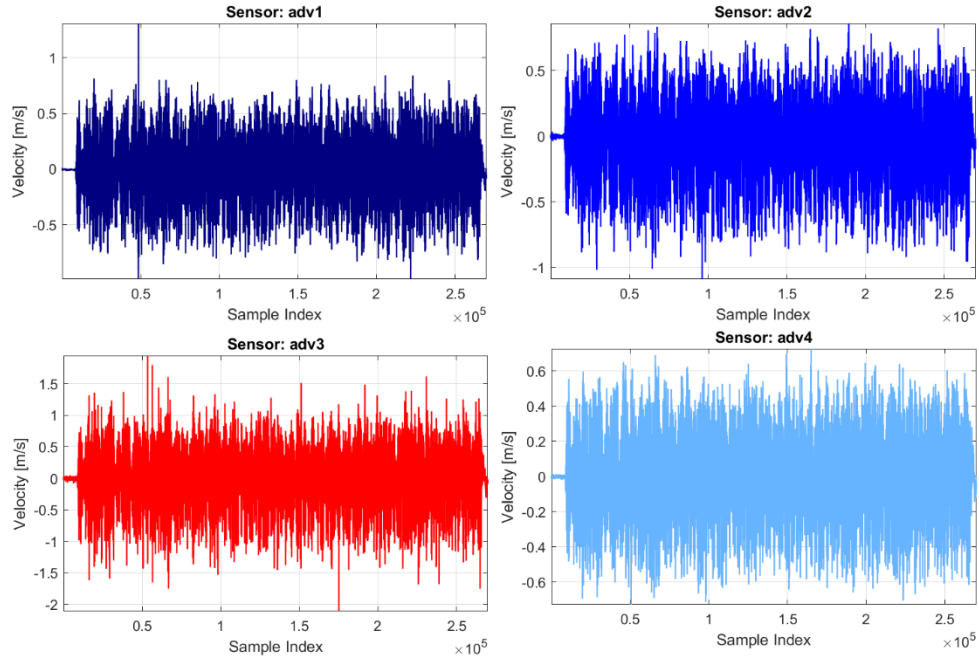


Figure 90 – Example of orbital velocity timestep (HMS test).

For the monopile tests (MS and MD), its presence results in a slight enhancement of local velocities mainly due to streamline contractions. Table 43 shows amplifications of approximately 10% and 20% for $U_{m,s}$ and $U_{m,max}$, respectively, relative to incident conditions. As for the hybrid structure setup, when the WEC flaps are fixed (simulating survival mode), the structure acts as a bluff body, resulting in $\alpha_{U_{m,max}} \approx 1.40$ and $\alpha_{U_{m,max}} \approx 2.30$. When the flaps are loose (HMS and HMD), the values recorded for the significant orbital velocity are similar to those in the HFS and HFD tests (Table 42 and Figure 91). However, for the $U_{m,max}$, the $\alpha_{U_{m,max}}$ does not reach values above in the same order of magnitude as in HFS and HFD, reflecting the converter's absorption capacity to attenuate some of the turbulence when compared to the fixed paddles hybrid setup, which seems to enhance velocities registered close to the scour protection through reflection, contraction, and diffraction.

Table 42 – Significant and maximum orbital bottom velocities.

Test	ADV1		ADV2		ADV3		ADV4	
	$U_{m,s}$ [m/s]	$U_{m,max}$ [m/s]	$U_{m,s}$ [m/s]	$U_{m,max}$ [m/s]	$U_{m,s}$ [m/s]	$U_{m,max}$ [m/s]	$U_{m,s}$ [m/s]	$U_{m,max}$ [m/s]
MS	0.405	0.883	0.394	0.842	0.446	1.042	0.394	0.728
HFS	0.413	0.918	0.402	0.834	0.579	2.115	0.533	1.069
HMS	0.411	0.999	0.391	0.883	0.567	1.881	0.357	0.736
MD	0.403	0.912	0.419	0.877	0.452	1.098	0.398	0.748
HFD	0.414	0.943	0.401	1.130	0.565	2.194	0.354	0.788
HMD	0.418	1.396	0.403	0.904	0.566	2.031	0.365	0.820

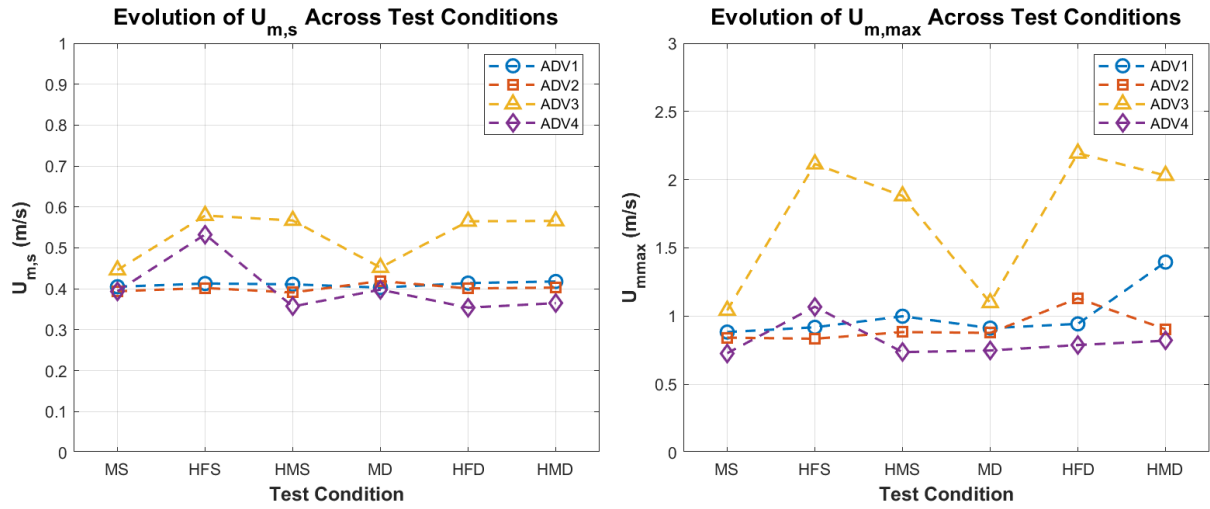


Figure 91 – Orbital bottom velocities evolution.

The values measured on the downstream side of the model (ADV4) reveal an expected behaviour. For the monopile (MS and MD), $U_{m,s}$ and $U_{m,max}$ remain stable and practically similar to the incident conditions (0.97–0.99). However, for most hybrid tests, an approximately 13% reduction in $U_{m,s}$ was observed. This indicates that the WEC produces a sheltering effect by creating a "shadow zone" of reduced velocities and turbulence on the leeside of the model, except for the HFS test, where local turbulence enhancement was still observed, possibly due to blockage effects or an error in the measurement device.

Table 43 – Orbital bottom velocity modification relative to incident conditions.

Test	ADV2/ADV1		ADV3/ADV1		ADV4/ADV1	
	$\alpha U_{m,s}$	$\alpha U_{m,max}$	$\alpha U_{m,s}$	$\alpha U_{m,max}$	$\alpha U_{m,s}$	$\alpha U_{m,max}$
MS	0.97	0.95	1.10	1.18	0.97	0.82
HFS	0.97	0.91	1.40	2.30	1.29	1.16
HMS	0.95	0.88	1.38	1.88	0.87	0.74
MD	1.04	0.96	1.12	1.20	0.99	0.82
HFD	0.97	1.20	1.36	2.33	0.86	0.84
HMD	0.96	0.65	1.35	1.45	0.87	0.59

As previously mentioned, despite the need to increase the water depth to accommodate the hybrid structure requirements, the wave height was also increased to maintain incident flow characteristics as similar as possible to those tested in the monopiles, enabling a direct comparison. Table 44 provides the $\alpha U_{m,s}$ and $\alpha U_{m,max}$ ratios for each pair of monopile–hybrid structure in the different setups. Some of the previous observations remain valid. As expected, the velocities registered offshore and in the vicinity of the model remained stable across all test series, and the transmitted conditions were slightly reduced (~10%), independent of the structure tested. As for the measurements made on top of the scour protection, it was concluded that:

- The hybrid structure consistently leads to $U_{m,s}$ values that are 25–27% higher than those registered for the monopile tests.

- The contrast is even more severe for $U_{m,max}$, where the hybrid structure generates peak velocities between 80 to 100% higher than those of the monopile.

In summary, the results highlight once more that transforming a standard monopile into a hybrid structure fundamentally alters the near-field hydrodynamics around the foundation and its scour protection, enhances turbulence, and elevates the erosive potential. Overall, the hybrid structure transitions the flow regime from a mild contraction (characteristic of monopiles) to a high-amplification blockage regime. These amplified conditions correlate directly with the increased damage observed in the physical model, supporting that current scour protection design methods may not be prepared or suitable for hybrid geometries.

Table 44 – Orbital bottom velocity amplification between monopile and hybrid structure tests.

Test	ADV1		ADV2		ADV3		ADV4	
	$\alpha U_{m,s}$	$\alpha U_{m,max}$	$\alpha U_{m,s}$	$\alpha U_{m,max}$	$\alpha U_{m,s}$	$\alpha U_{m,max}$	$\alpha U_{m,s}$	$\alpha U_{m,max}$
MS vs HFS	1.01	1.13	0.99	1.05	1.27	1.81	0.91	1.01
MS vs HMS	1.01	1.13	0.99	1.05	1.27	1.81	0.91	1.01
MD vs HFD	1.03	1.03	0.96	1.29	1.25	2.00	0.89	1.05
MD vs HFD	1.04	1.53	0.96	1.03	1.25	1.85	0.92	1.10

7.4. KC–MOB ANALYSIS

The applicability of the recently proposed scour-prediction method by Broekema *et al.* (2024), which was applied in Chapter 4, was assessed to analyse the dimensionless scour depth in the large-scale tests. This model introduces a system based on two physically interpretable parameters: KC_{tot} , which represents the hydrodynamic forcing relative to the structure, and MOB_{top} , which represents the hydraulic load relative to the armour layer's resistance. Given the absence of currents in this experimental campaign, KC_{tot} is equivalent to the wave-induced KC number.

A comparison between the measured S/D and the predictions ($S/D_{predicted}$) derived from Equation (8) is presented in Table 45, using both the ADV1 and ADV3 data. For ADV1, KC_{tot} and MOB_{top} were estimated using the script described in Chambel *et al.* (2025). For ADV3, only MOB_{top} was estimated using the same script, since KC_{tot} already considers the orbital velocity measured at the top of the scour protection. The results highlight a distinct contrast in the Equation (8) ability to predict the measured results. When using the ADV1 data, the formulation systematically underestimates S/D across all configurations, particularly in hybrid tests. For those tests, the formula fails to capture the intensified scour deformation of the scour protection. These underestimations align with the results of the small-scale tests and suggest that, even for standard monopiles, the formula's accuracy may be diminished when applied to incident hydrodynamic conditions.

As aforementioned, Chen *et al.* (2022) and Gong *et al.* (2023, 2025) observed that prediction models tend to underestimate scour depths, particularly in irregular wave-only conditions, due to scale effects. Gong *et al.* (2025) proposed redefining the KC number using $U_{m,max}$ to improve accuracy. However, since the ADV3 data captured the amplification of turbulence acting on the scour protection, it was decided to use them to recalibrate the prediction values. The use of the ADV3 data significantly improved the accuracy, bringing $S/D_{predicted}$ closer to the measured values. For the static protection tests, the values remained slightly under the measured results. As for the dynamic protection tests, it predicted the MD test result with high precision but substantially overestimated the scour protection deformation in the hybrid tests. This overestimation may be related to the high velocities combined with the smaller

rock size used for the armour layer, resulting in high MOB_{top} values, triggering a spike in the $S/D_{predicted}$. This indicates that the Broekema *et al.* (2024) prediction model can identify increased deformation risk when using measured data directly on top of the scour protection armour layer, but may be overly sensitive to high mobility ratios.

Table 45 – Relative scour depth comparison with Broekema *et al.* (2024)’s Equation (8).

Test		ADV1			ADV3		
Ref.	S/D	$S/D_{predicted}$	KC_{tot}	MOB_{top}	$S/D_{predicted}$	KC_{tot}	MOB_{top}
MS	0.086	0.047	6.23	0.42	0.052	6.39	0.43
HFS	0.164	0.048	6.24	0.42	0.124	8.29	0.60
HMS	0.131	0.047	6.21	0.42	0.116	8.12	0.58
MD	0.167	0.135	6.20	0.80	0.161	6.47	0.85
HFD	0.199	0.140	6.25	0.81	0.373	8.09	1.18
HMD	0.223	0.145	6.31	0.82	0.376	8.11	1.19

When classifying scour protections according to the deformation classes proposed by Broekema *et al.* (2024), the contrast between the observed deformation patterns in Table 47 and the theoretical classes highlights the inherent challenges in applying this classification system. The deformation class system, while associating wave-only conditions with Class 6 (deformation mainly upstream with a single shallow downstream deformation point, associated with horseshoe vortex dominance), when considering the calculated KC_{tot} and MOB_{top} , pushes the classification into current-dominated zones (Classes 4–5) on their charts (dominance of lee-wake vortices and downstream deformation). However, this downstream deformation pattern was reported by Chen and Li (2018), Chen *et al.* (2022), and Gong *et al.* (2023, 2025), where lateral and downstream deformation were observed for wave-only conditions in large-scale monopile testing.

For the static protection tests, the visual inspection of the photographic and DTM register, along with the analysis of overlapping results, indicates that the tests fall within Class 1 (negligible/spot deformation) or Class 3 (evenly distributed upstream/downstream deformation). For the dynamic protection tests, the damage pattern fits with the pattern description made by Chen and Li (2018), Chen *et al.* (2022), and Gong *et al.* (2023, 2025):

- For the monopile test (lower KC), the deformation occurs on both sides of the foundations.
- For the hybrid tests (higher KC), the deformation increases on the sides and starts to shift to the downstream region. Additionally, and not observed by Chen and Li (2018), Chen *et al.* (2022), and Gong *et al.* (2023, 2025), a single upstream deformation point appears, probably due to the downflow and jetting caused by the WEC’s front paddle.

Therefore, the damage observations for the MD test forced a Class 3 classification. As for the hybrid structures (HFD/HMD), the classification based on the calculated KC_{tot} and MOB_{top} , using the ADV3 data, they fall out of scope (Figure 92), and based on damage patterns observed it matches an inverse Class 6 classification (downstream deformation instead of upstream, and a single upstream deformation point instead of a downstream deformation point). This discrepancy (Table 46) points to classification’s ambiguity and indicates that, while both parameters have the potential to serve as relevant indicators of scour deformation, the system may require refinement for hybrid structures.

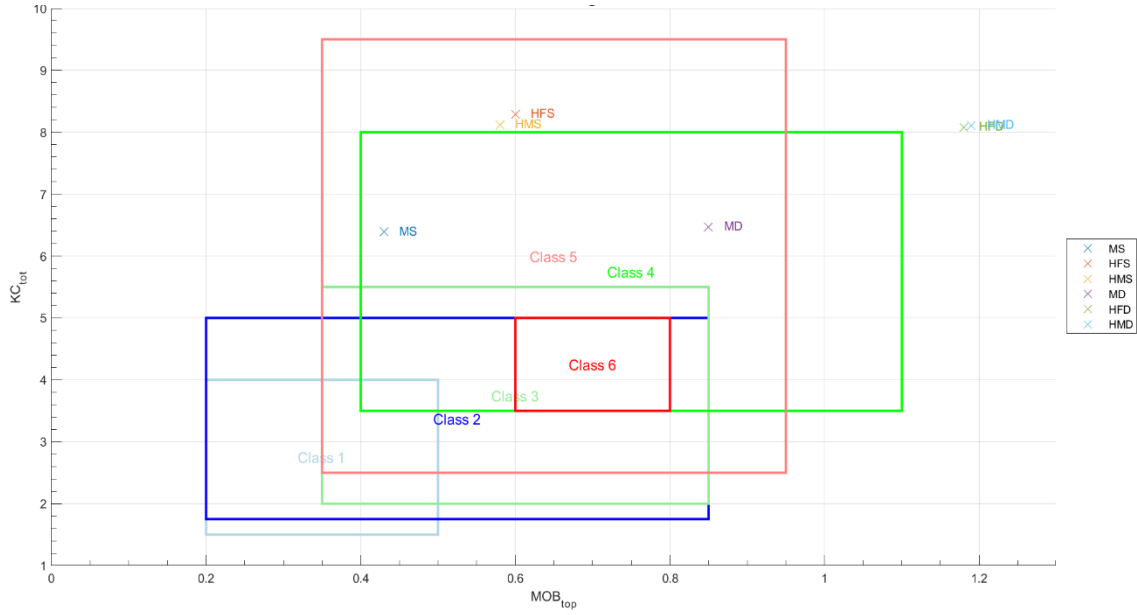


Figure 92 – Deformation classes for large-scale tests (ADV3).

Table 46 – Deformation class according to the criteria defined by Broekema *et al.* (2024).

Test	Deformation Class Assessment	ADV3 (Figure 92)
MS	Class 1	Class 4-5
HFS	Class 1 (or 3)	Class 5
HMS	Class 1	Class 5
MD	Class 3	Class 4-5
HFD	Inverse Class 6	-
HMD	Inverse Class 6	-

7.5. COMPARATIVE PERFORMANCE OF S/D PREDICTIVE MODELS

7.5.1. EVALUATION OF EXISTING S/D EQUATIONS

S/D assessed the predictive capability of other existing empirical formulae against the four other equations found in the literature. Webb and Matheus (2014) and Mustafa (2021) base their formulas on Sumer *et al.* (1992), and their results provide an extensive analysis of different experimental datasets for slender and large piles under wave-induced conditions. Jalloul *et al.* (2026) proposed a formula based on other parameters, such as U_{cw} and D/L , to reduce the dependency on the KC number. The evaluation was also conducted with the incident conditions (ADV1, Table 47) and local near-field conditions measured directly on top of the scour protection (ADV3, Table 48). This dual-approach analysis isolates the converter's impact on prediction accuracy. It tests the hypothesis that local flow amplification is the primary driver of the observed discrepancies in predicted values for the hybrid structure tests. The equations used during the analysis are presented as follows:

- Webb and Matheus (2014):

$$\frac{S}{D} = 1.3 \cdot (1 - e^{-0.035(KC-5)}); KC \geq 5 \quad (24)$$

- Mustafa (2021):

$$\frac{S}{D} = 1.3 \cdot (1 - e^{-0.022(KC-4)}); KC \geq 4 \quad (25)$$

- Jalloul *et al.* (2026):

$$\frac{S}{D} = 1.9 \cdot (1 - e^{(-A_n \cdot (KC^{0.5} - B_n^{0.5}))}); KC > B_n \quad (26a)$$

$$A_n = 0.06 + 4U_{cw}^{\left(\frac{1}{KC^{0.5}+4}\right)} \quad (26b)$$

$$B_n = \left[3 - 2.8 \cdot \tanh \left(7 \cdot \left(\frac{D}{L} \right)^{0.75} \right) \right] \cdot e^{-6U_{cw}} \quad (26c)$$

The results obtained under incident conditions (Table 47), as in the previous sub-chapter, indicate an overall underprediction of S/D at the system level. Webb and Matheus (2014) and Mustafa (2021) significantly underestimate the S/D by factors of 2-5. Conversely, a recent model by Jalloul *et al.* (2026) overpredicts deformations in static protection tests but underpredicts them in dynamic protection tests. This confirms that solely relying on incident hydrodynamic conditions can lead to significant inaccuracies, as near-bed turbulence and orbital velocity are underestimated, particularly in hybrid structure setups. Following the same logic as the Broekema *et al.* (2024) $KC_{tor}-MOB_{top}$ analysis, incorporating local hydrodynamic conditions measured at the ADV3 location significantly improves predictive performance, particularly for the most recent empirical model. The Jalloul *et al.* (2026) equation achieves remarkable accuracy across all tests, including hybrid structure setups, demonstrating that the KC number's dependency can provide considerable benefits. The only exception is the MS test, where an approximate 52% overestimation was obtained. On the other hand, despite some improvements, the remaining models are only able to improve accuracy for the MS and HFS (Webb and Matheus, 2014) and for the MS (Mustafa, 2021).

Table 47 – S/D comparison to other scour depth prediction equations using ADV1 data.

Test		Webb and Matheus (2014)	Mustafa (2021)	Jalloul <i>et al.</i> (2026)
Ref.	S/D	$S_{predicted}/D$	$S_{predicted}/D$	$S_{predicted}/D$
MS	0.086	0.036	0.046	0.118
HFS	0.164	0.041	0.049	0.120
HMS	0.131	0.040	0.048	0.120
MD	0.167	0.035	0.045	0.117
HFD	0.199	0.042	0.049	0.121
HMD	0.223	0.044	0.051	0.122

It is necessary to acknowledge that, opposite to the Broekema *et al.* (2024) model, the predictive equations used during this analysis were derived initially to assess scour around unprotected monopiles, rather than to predict the deformation of a rubble-mound scour protection. Consequently, a direct comparison can be limited, as the erosion of the unprotected seabed can differ from the armour layer material's response to scour. Moreover, while scale and model effects are undeniably present in physical

modelling, the data suggest that the added complexity induced by hybrid structures in the flow patterns and turbulence acting directly on the scour protection may be the primary source of error. Therefore, it can be concluded that while Jalloul *et al.* (2026) yield reasonable approximations under these specific conditions, the development of new equations specifically tailored for protected standard, complex, and hybrid structures is necessary to accurately predict scour deformations and characterise the flow amplifications that drive the erosive process.

Table 48 – S/D comparison to different scour depth prediction equations using ADV3 data.

Test		Webb and Matheus (2014)	Mustafa (2021)	Jalloul <i>et al.</i> (2026)
Ref.	S/D	$S_{predicted}/D$	$S_{predicted}/D$	$S_{predicted}/D$
MS	0.086	0.062	0.061	0.131
HFS	0.164	0.141	0.107	0.167
HMS	0.131	0.134	0.103	0.164
MD	0.167	0.065	0.063	0.132
HFD	0.199	0.133	0.102	0.164
HMD	0.223	0.134	0.103	0.164

7.5.2. S/D FORMULATION PROPOSAL

As existing design standards and predictive formulas can be conservative and unable to capture the complexities of WEC-induced enhanced flow, this research seeks to address the need for an approach that reduces the disparities between predictive and measured results. Two of the main critical aspects identified are the misrepresentation of flow amplifications and of the armour layer behaviour. Consequently, a new set of equations to assess scour deformation (S/D) was developed for each structure – Equation (27) for protected standard monopiles and Equation (28) for protected hybrid monopiles. Both were derived from the combined dataset that included results from both the small-scale (Chapter 4) and large-scale (Chapter 7) experimental campaigns. To ensure the formulation’s applicability across different geometric scales and to mitigate scale effects, the equations were developed solely in terms of dimensionless parameters. Considering some of the equations and variables used and presented during the literature review and experimental testing analysis, KC_{tot} and MOB_{top} were selected parameters as foundational drivers since:

- **KC_{top}** : measures the wave-current contribution (U_m , T_p , U_c) relative to the foundation (D).
- **MOB_{top}** : measures the protection’s armour layer material resistive capacity (D_{50} , ρ_s) to the hydraulic loading.

As for the final parameter, current state-of-the-art formulations do not treat the scour protection thickness as a governing variable. Therefore, the proposed equations introduce the relative protection thickness ratio (t_s/d), which expresses the amount of “available” armour-layer material that can be eroded without compromising the filter, foundation, or seabed. The thicker armour layer offers greater reshaping capacity before failure.

The equations were specifically calibrated to capture the complex interactions among the hydrodynamic conditions, the scour protection, and the foundation. It should be highlighted that these formulations were estimated using a relatively limited number of data points specific to this research. For the large-scale tests, the calibration values were those obtained from the ADV3. Given the impossibility of directly measuring data above the scour protection, it is suggested to use the method of Broekema *et al.* (2024) to estimate KC_{tot} and MOB_{top} . However, while the equations may be case-specific, they contribute

to the optimisation of scour protection design for offshore hybrid structures. While the development of an empirical formula for the damage number was also explored, the resulting models exhibited inadequate R^2 and RMSE (Root Mean Square Error) values. The derivation process involved evaluating multiple regression models to identify the most suitable mathematical forms that best described the observed physical processes. In the end, both formulations followed a Multiplicative Power Law, which provided the most precise fit.

$$\frac{S}{D} = 4.05 \times 10^{-2} \cdot KC_{tot}^{0.58} \cdot MOB_{top}^{0.60} \cdot \left(\frac{t_s}{d}\right)^{-0.1} \quad (27)$$

$$\frac{S}{D} = 1.2 \times 10^{-6} \cdot KC_{tot}^{1.62} \cdot MOB_{top}^{0.61} \cdot \left(\frac{t_s}{d}\right)^{-2.72} \quad (28)$$

The proposed predictive equation for monopiles (Figure 93) shows a satisfactory correlation between predicted and measured values ($R^2=0.73$), with some slight scatter, with most data points falling within $\pm 25\%$ error margins. As for the hybrid structure, the proposed formulation demonstrates high accuracy, effectively capturing the amplified scour mechanisms driven by the WEC ($R^2=0.96$), with data points closely following the reference line, even at high S/D values. The scatter plot (Figure 94) confirms that the Multiplicative Power Law solves some of the problems related to extreme turbulence that other empirical formulations developed for unprotected monopiles are unable to describe accurately. Moreover, it partially validates the selection of the parameters as governing parameters for describing scour deformations along the scour protection. Nonetheless, further testing is required to develop stronger predictive equations and, if possible, to develop an equation that accurately predicts the damage number (S_{3D}) with less conservatism.

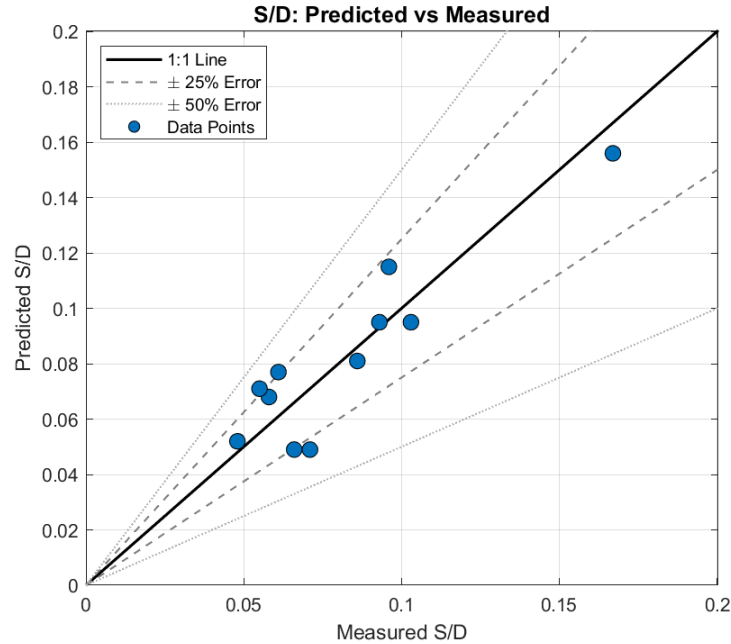


Figure 93 – Monopile S/D model performance evaluation: Equation (27).

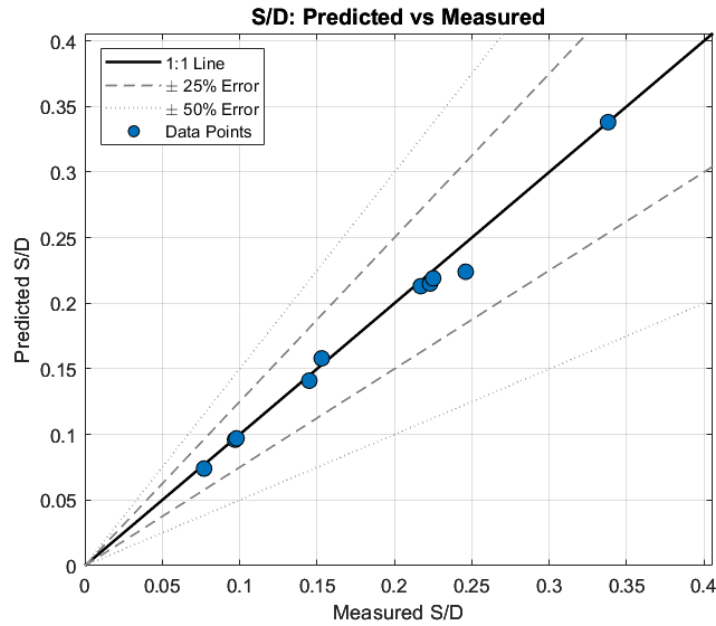


Figure 94 – Hybrid monopile S/D model performance evaluation: Equation (28).

7.5.3. S/D PREDICTIVE MODEL: COMPARISON AND VALIDATION

To rigorously validate the proposed scour prediction formulation, the measured vs predicted dimensionless scour depths were measured against the four empirical models analysed in this chapter: Webb and Matheus (2014), Mustafa (2021), Broekema *et al.* (2024), and Jalloul *et al.* (2026). Figure 95 provides a synthesis of the model's accuracy across the range of hydrodynamic conditions tested in the large-scale tests. For the $S/D_{\text{prediction}}$ values, only those obtained from the ADV3 reads were used.

The data points for Webb and Matheus (2014; blue circles) and Mustafa (2021; red crosses) consistently fall below the 1:1 line, particularly for $S/D > 0.15$ (associated with the hybrid structures). Most points lie outside the $\pm 25\%$ error margin and approach or exceed the -50% boundary. This visualises the systemic failure of these models to capture the intensified scour mechanisms driven by the WEC, confirming their unsuitability for hybrid geometries without significant modification. The Jalloul *et al.* (2026; magenta diamonds) generally cluster closer to the reference line and, despite some scatter, fall mainly within the $\pm 25\%$ error margin. However, a slight underestimation trend remains visible. Broekema *et al.* (2024; black dots), show high variation, with data points below $S/D < 0.2$ being close to the reference line and within the $\pm 25\%$ error margin, but the remaining values falling way outside the $+50\%$ error margin line, showing an overestimation of the model to the amplified flow patterns induced by the hybrid structure.

The proposed equations in this thesis, represented by the orange dots, provide a superior fit to the experimental dataset compared to those in the existing literature. It maintains consistent accuracy, with data points closely following the 1:1 line, from lower S/D values (monopiles with static protection) to higher S/D values (dynamic protections applied to the hybrid structures). This corroborates the premise that relying on a single generalised equation to characterise the complex scour phenomena associated with such structurally distinct structures may be inadequate. Implementing different equations, calibrated to account for the specific structural features that exert considerable influence on hydrodynamic amplifications and induced turbulence, constitutes a more reasonable premise. The

comparative analysis confirms that, under the conditions tested in this study, the proposed formulations represent a significant advancement in predicting scour depths for protected monopiles and hybrid offshore structures. By achieving a reasonable to high R^2 coefficient and maintaining all predictions within $\pm 25\%$ of the actual value, the proposed model addresses some of the flaws of other equations and represents one of the few alternatives for scour prediction on rubble-mound countermeasures, the first for hybrid structures.

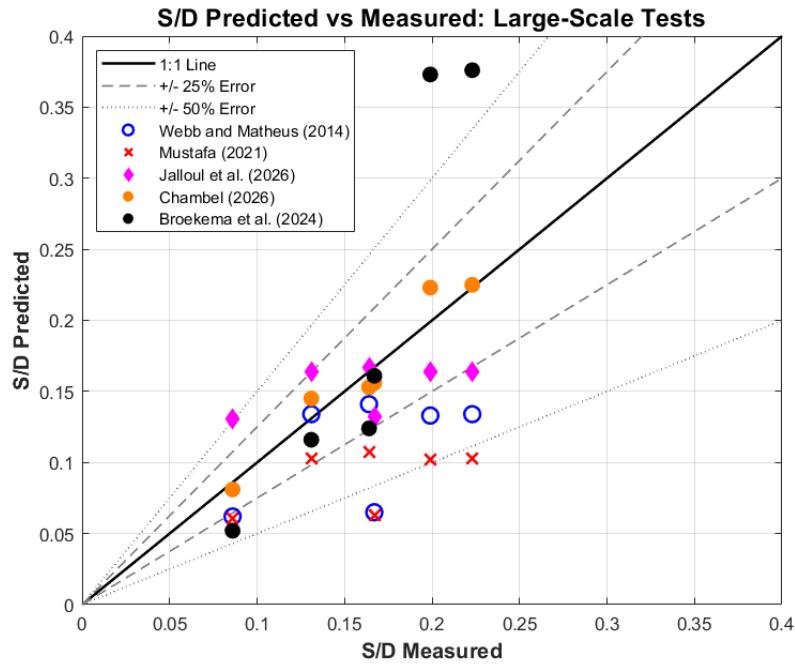


Figure 95 – Applicability and comparison of different S/D formulas.

7.6. WAVE TRANSMISSION AND WAVE REDUCTION COEFFICIENTS

The integration of a WEC into a standard offshore foundation introduces complex hydrodynamic interactions and significantly alters flow patterns. Consistent with the methodology followed in previous chapters, the K_T and K_{red} coefficients were analysed to quantify the hydrodynamic impact of the hybrid structure relative to a monopile. While the test results allow an analysis of the K_T across all configurations, a direct comparison of K_{red} between the monopile and the hybrid structure was constrained by the differences in the hydrodynamic conditions used. However, a comparison between the hybrid model with fixed flaps and with moving flaps was conducted to provide insights into the influence of the converter's paddle oscillation.

Regarding the wave transmission coefficient, the monopile tests consistently yielded values near 100% (Table 49), indicating minimal interference with incident wave propagation. This behaviour is attributed to the monopile's narrow cross-section, which allows waves to pass with negligible attenuation – deviations were observed to be less than 2%. This confirms the limited capacity for sheltering in the isolated pile. In comparison, small-scale testing performed in Chapter 4 showed slightly higher variation, approximately 5%. Conversely, for the hybrid monopiles, the presence of the OSWEC enhanced the structure's sheltering capacity, resulting in a measurable reduction in K_T . Specifically, a 10% deviation was observed when the paddles were fixed, compared with 6% when the paddles were

completely loose. Notably, both values are significantly lower than the 25% wave reduction reported during the small-scale testing in Chapter 4. While it was expected that a converter with a fully operational PTO system would achieve higher attenuation, the discrepancy between the two studies suggests that the more severe hydrodynamic conditions in the large-scale experiments may have compromised the WEC's hydrodynamic performance compared to that tested in the small-scale experiments. Moreover, scale and model effects may also influence the incongruities observed. Future research should aim to replicate identical conditions across scales to assess whether the converter can enhance leeside wave reduction under comparable hydrodynamic regimes.

Table 49 – Wave transmission coefficient (K_T) for large-scale tests.

Test	No. of Waves	K_T (%)
MS	3000	98.4
HFS	3000	89.2
HMS	3000	93.6
MD	3000	99.3
HFD	3000	89.9
HMD	3000	94.3

The analysis of the reduction coefficient for the hybrid monopile configurations reveals slight negative values on both the onshore and offshore sides of the converter (Table 50). This suggests a negligible wave enhancement of up to 2% on the offshore side and approximately 6% on the onshore side when the paddles are in motion. This result is consistent with the experimental setup, in which the paddles were subjected to minimal damping, thereby offering little resistance to the incoming wave. When the paddles were fixed, the WEC demonstrated a higher sheltering effect. Theoretically, optimising the damping coefficient for specific wave conditions could yield a net reduction in the wave height, thereby mitigating the flow amplification that drives local scour.

Table 50 – Wave reduction coefficient (K_{Red}) for hybrid structures for large-scale tests.

Test	No. of Waves	Offshore K_{Red} (%)	Onshore K_{Red} (%)
HFS vs HMS	3000	-1.4	-6.0
HFD vs HMD	3000	-2.0	-6.5

In conclusion, the results for the hybrid structure demonstrate a serious trade-off: despite a reduction in transmitted wave height relative to the incident wave, scour damage to the protection layer increased. This indicates that including a WEC may exacerbate near-field seabed instability while attenuating far-field wave energy. Consequently, in the future, hybrid structure designs should consider the tip clearance between the device and the seabed and the precise tuning of the damping coefficient to the incident hydrodynamic conditions to prevent detrimental scour effects. Furthermore, selecting the correct scour protection strategy, whether static protections, increasing the thickness of dynamic armour layers, or even selecting other scour countermeasures, requires rigorous evaluation to withstand the amplified turbulence generated by the hybrid structure.

7.7. CONCLUSIONS

The large-scale experimental campaign presented in this chapter was conducted to validate and expand upon the findings of small-scale testing, explicitly addressing the hydrodynamic influence of a fully operational WEC on scour protection stability. Although the hydrodynamic conditions do not allow a straightforward comparison between the two scales or between the configurations tested during the large-scale testing, the setup confirmed the proposition that transforming a standard monopile into a hybrid structure fundamentally alters the near-field flow regime. In fact, placing an ADV above the scour protection also allowed the direct quantification of the amplification induced by the converter due to blockage effects and its complex structural features. A significant increase in near-bed orbital velocities (27%) and peak orbital velocities (100%) was registered, exceeding those observed for monopiles. When compared to the incident conditions used for each test, those values increase to approximately 40% ($U_{m,s}$) and 130% ($U_{m,max}$), thereby confirming the intensification of the main scour mechanisms that current design standards fail to capture.

As for the application of the overlapping-circle methodology, it proved once again to be a robust tool for quantifying damage distribution, including in large-scale models, despite its increased computational demand. The sensitivity analysis regarding the grid ratio reinforced the conclusions from previous chapters, confirming that a sub-area of $4D_{n50}^2$ represents the most balanced threshold for identifying local failure. However, the analysis showed that, for hybrid structures whose protection suffered higher damage rates, a slightly lower resolution can still provide a good representation of the critically damaged zones, while reducing computational demands and the likelihood of outliers and extreme values.

The comparison between static and dynamic protection strategies revealed a critical behavioural divergence. While the “compliance” of the moving WEC flaps reduced damage to the static protection (acting as a damper), it exacerbated damage to dynamic protection, as constant oscillatory turbulence led to rapid erosion of the armour layer, preventing the smaller material from recovering, an identified ability associated with these countermeasures.

In summary, the novel contributions and main takeaways from this large-scale study are highlighted below:

- **Quantification of the Flow Amplification:** The hybrid structure consistently generated significant and maximum orbital velocities 25–27% and 80–100% higher, respectively, than those registered in the monopile tests. This confirms that the WEC acts as a massive bluff body, drastically increasing the erosive potential at its foundation.
- **Divergent Response of Protection Types to WEC Motion:** A distinct effect was observed across WEC operational modes. For static protection, moving flaps reduced damage compared to the survival mode. Conversely, for dynamic protection, the moving flaps increased damage because persistent turbulence disrupted the reshaping ability that dynamic protection provides.
- **Inadequacy of Existing Design Formulae:** Existing empirical models (De Vos *et al.*, 2012; Broekema *et al.*, 2024) proved to be insufficient to capture the effects induced by hybrid configurations. De Vos *et al.* (2012) underestimated static damage and, while overestimating dynamic damage, failed to predict the correct rank order of failure. Similarly, Broekema *et al.* (2024) systematically underestimated scour depths when using incident wave data, requiring local velocity measurements to achieve reasonable accuracy.
- **Proposal of New Predictive Formulations:** A new set of equations to predict S/D was derived, adding the protection thickness as the governing parameter. The proposed Multiplicative Power Law formulation achieved reasonable accuracy. Given the small dataset, further testing is

necessary to determine whether it effectively bridges the gap between standard and complex offshore structures.

- **The Wave Attenuation vs Scour Trade-off:** The results demonstrated a serious engineering trade-off – while the hybrid structure successfully attenuated far-field wave energy (reducing K_T by 6–10%), it exacerbated near-field seabed instability. This indicates that the potential benefits of coupling a WEC to an offshore structure come at the cost of increased structural risk to the foundation.

To advance the design of offshore foundations and offshore hybrid structures, future research should focus on replicating and extending test conditions and datasets, and on adding long-term fatigue testing beyond 3000 waves to assess whether the "reshaping" of dynamic protections is sustainable or a precursor to progressive failure. Additionally, the strong correlation between local velocity amplification and damage underscores the need for high-fidelity CFD modelling. Such models should aim to quantify the pressure gradients induced by the paddle motion, providing the necessary data to refine future design guidelines.

8. Conclusions and Future Developments

8.1. INTRODUCTION

This chapter presents a comprehensive synthesis of the key findings, methodological advances, and challenges encountered in the study of scour protection for offshore hybrid structures, bridging the gap between small- and large-scale experiments. The research initially aimed to optimise protective countermeasures and propose a novel damage number equation that would account for the enhanced effects and increased complexity associated with complex and hybrid structures. However, as the study progressed, the focus shifted to improve understanding of hydrodynamic interactions among offshore structures, energy converters, and protective solutions. Consequently, novel predictive equations were proposed for the dimensionless scour depth, while acknowledging their inherent limitations as a primary descriptor for the overall behaviour and state of a scour protection. Overall, this research combined a probabilistic analysis of *in situ* data, small-scale physical model testing of (hybrid) monopiles and (hybrid) jackets, statistical analysis of damage for complex foundations, and large-scale testing of a fully operational offshore hybrid structure model.

The research progression was driven by gaps identified in the literature review and by practical challenges arising from needs in the offshore engineering and renewable energy sectors. Chapter 2 contextualised state-of-the-art scour mitigation techniques and identified a lack of specific design guidelines and studies for protected complex and hybrid structural systems. Chapter 3 details the designs of the physical models and instrumentations used to capture hydrodynamic and morphological data for the experimental research performed at FEUP and OSU. Chapters 4 and 5 presented small-scale studies of hybrid and complex offshore structures models to assess and analyse the influence of complex/hybrid structures on scour, while validating the overlapping-circle method as a reliable tool for measuring scour across multiple structures and geometries. Chapter 6 focused on the statistical analysis of damage for complex foundations, proposing a calibration protocol to define failure and static thresholds based on mesh resolution and introducing a global scour evaluation framework based on spatial-volumetric material loss from scour protection. Finally, Chapter 7 reported the main findings from one of the first large-scale experimental studies performed for a hybrid offshore structure, quantifying flow amplification effects and proposing new predictive formulas.

8.2. FINDINGS AND CONTRIBUTIONS

The research conducted in this thesis has led to several findings regarding the behaviour of scour protections for hybrid offshore structures, contributing to the advancement of the scour and offshore engineering fields by:

- **Assessing the impact of hybrid structures:** The main finding is the identification of a severe engineering trade-off between wave attenuation and scour, in hybrid structures. While coupling a WEC to an offshore structure successfully attenuates leeward wave heights, the device's oscillatory motion significantly intensifies scour.
 - Small-scale tests suggested, large-scale tests confirmed: hybrid structures increased near-bed orbital velocities by 25–27% and enhanced peak velocities by up to 100%, then those observed for standard monopiles. Damage rates for hybrid structures were consistently higher, despite not being as catastrophic as the small-scale test suggested. These findings are limited to the FOSWEC device. However, it is confirmed that a case-to-case approach is required when designing scour protections for hybrid structures, whose scour mechanisms can be significantly enhanced depending on the WECs influence in the local hydrodynamics.
- **Advancing the damage quantification methodologies:** This work successfully adapted and validated the overlapping-circle method for complex/hybrid structures and non-standard scour protection shapes, overcoming the limitations of traditional fixed-area methods.
 - A strong correlation was established between the damage number and the grid ratio. The research found that the failure criterion of den Boon *et al.* (2004), $A_{sub}=4D_{n50}^2$, remains the most balanced threshold for identifying local failure across different foundation types.
 - A novel protocol was developed to calibrate static and failure thresholds for complex foundations based on the overlapping-circle mesh resolution. This ensures that high- and low-resolution analyses can be harmonised for consistent decision-making.
 - A new volumetric-based framework was proposed to distinguish between localised spot deformations and global structural failure, allowing for more rational maintenance decisions.
- **Reevaluating (in)adequacy of existing guidelines and proposing new models:** experimental results confirmed that existing design formulas and stability thresholds, such as the ones proposed by De Vos *et al.* (2012), systematically fail to predict and/or describe damage mainly to complex and hybrid structures, as they fail to account for WEC-induced turbulence and overcomplex structural features.
 - Alternative ratios such as the S/t_s and S_{3D}/n_s , based on the thickness of the scour protection, were proven to be more reliable indicators of the protection performance than standard absolute thresholds, as they take into consideration the amount of “available” armour-layer material that can be eroded without compromising the protection and the foundation.
 - A set of new equations for predicting S/D in protected monopile and hybrid monopile structures was derived. By incorporating the relative protection thickness (t_s/d) into the KC_{tot} and MOB_{top} variables used by Broekema *et al.* (2024), the formulations showed promise and high accuracy for conditions tested for the hybrid structure.

8.3. FUTURE WORK RECOMMENDATIONS

Throughout this research, significant progress has been made in understanding hybrid structures and the major drawbacks they entail. However, this constitutes only a small contribution to a vast field of future research on scour and scour protection for hybrid structures. The following topics summarise key aspects and future directions to improve and optimise the scour protection design for standard, complex, and hybrid offshore structures:

- **Experimental Data:**
 - **Dataset expansion:** the replication and extension of the current dataset should be considered as a priority to transition the study from a case-specific to a robust, generalised framework. Expanding the dataset would improve damage characterisation, enhance understanding of failure modes, isolate scale effects from model effects, and improve future design guidelines.
 - **Long-term damage:** The test matrix was limited to 3000 waves. Future research should extend to 5000+ waves to assess whether the "reshaping" observed in dynamic protections is a sustainable equilibrium or a precursor to progressive failure.
 - **Hydrodynamic conditions:** This study focused on waves-only and co-directional waves and currents. Future research must expand the hydrodynamic conditions to include current-only and transverse/counter-directional waves and currents to determine whether flow asymmetry generates distinct damage patterns and deformations.
 - **WEC devices and parameters:** The influence of tip clearance and damping should be determined by systematically varying. Large-scale results suggested that WEC motion can either mitigate or exacerbate damage, depending on the protection type (static vs dynamic) – this interaction warrants a dedicated parametric study. Moreover, additional converters should be used to determine whether incremental structural risk is case-specific to the OSWEC or systematic across all device types.
- **Numerical Modelling:**
 - **High-Fidelity CFD models:** The strong correlation between local velocity amplification and damage necessitates the development of high-fidelity CFD models. These models should aim to quantify the pressure gradients and bed shear stresses induced by the paddle motion, which can be extremely difficult to measure in small-scale physical models and could even have an unwanted intrusive effect in large-scale setups.
- **Design and Validation:**
 - **Statistical framework validation:** The proposed statistical frameworks and threshold calibration protocols proposed for a complex geometry foundation and scour protection should be validated against extensive physical model and *in situ* datasets to refine the correction factors for prototype-scale monitoring.
 - **Unified design tool:** Further testing is required to consolidate, adjust, or improve the proposed equations into a unified design tool that can universally optimise the design and prediction of dynamic scour protections for standard, complex, and hybrid structures.

Despite the complexity of the challenges encountered, this work makes a solid contribution to scour research. While hybrid structures undeniably induce complex turbulence amplifications that increase

the potential for damage, this thesis demonstrates that these risks can be managed through optimised countermeasure design. This finding confirms that implementing hybrid structures may be feasible in the future, potentially essential for increasing renewable energy production and/or reducing the spatial footprint of offshore wind farms. In conclusion, this thesis advanced knowledge by addressing gaps in the literature, proposing predictive/design tools for dynamic scour protection, and highlighting some of the most pressing future challenges. It paves the way for continued research and development, supporting the creation of resilient scour protection systems that safeguard offshore wind turbines and advance the future of clean energy.

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Appendix I – Chambel *et al.* (2022)



Probabilistic Assessment and Comparison of Scour Protections at Horns Rev 3 and Egmond aan Zee Offshore Wind Farms

João Chambel, Researcher, Faculty of Engineering of University of Porto (FEUP) and Interdisciplinary Center of Marine and Environmental Research (CIIMAR), Porto, Portugal; email: up201304674@edu.fe.up.pt

Tiago Fazerres-Ferradosa, Assistant Professor, Faculty of Engineering of University of Porto (FEUP) and Interdisciplinary Center of Marine and Environmental Research (CIIMAR), Porto, Portugal; email: tferradosa@fe.up.pt

Rui Figueiredo, Senior Researcher, Faculty of Engineering of University of Porto (FEUP) and Interdisciplinary Center of Marine and Environmental Research (CIIMAR), Porto, Portugal; email: ruifig@fe.up.pt

Paulo Rosa-Santos, Associate Professor, Faculty of Engineering of University of Porto (FEUP) and Interdisciplinary Center of Marine and Environmental Research (CIIMAR), Porto, Portugal; email: pjrsantos@fe.up.pt

Francisco Taveira Pinto, Full Professor, Faculty of Engineering of University of Porto (FEUP) and Interdisciplinary Center of Marine and Environmental Research (CIIMAR), Porto, Portugal; email: fpinto@fe.up.pt

ABSTRACT: Offshore wind foundations have seen a remarkable growth in over the last three decades. Up to date, this growth has been mainly registered in North Sea locations, where water depths do not exceed 30 m and monopile diameters typically range between 4 to 9 m. In these cases, scour phenomena can be a main reason for structural instability and fatigue induced damage, thus there is often a need to apply scour protection. Given the complexity and uncertainties of scour phenomena, the design of scour protection is mostly based on semi-empirical formulations. These often result in conservative design, which in turn leads to excessive costs when installing offshore wind foundations. To account for the uncertainty in scour protection design and to assess the reliability of existing solutions, recent developments have been made regarding the application of probabilistic based analysis, which aim to either quantify the protection's reliability or to derive the median stone size associated to a target value for the probability of failure. However, there are few to almost no case studies reported in the literature concerning the reliability analysis of scour protection for offshore wind monopiles. Hence there is a need to extend this probabilistic analysis to a broad range of locations, to further improve their application for both design and median stone size optimization purposes. This research provides a study on the probabilities of failure at Horns Rev 3 and Egmond aan Zee offshore wind farms. The results show that the values of the probability of failure of a scour protection for the same design criterion can vary significantly depending on the site-specific conditions. Variations can be of two orders of magnitude, from 10^{-4} to 10^{-6} . Still, the probabilistic assessment is able to provide indications on the potential optimization of the median stone size. Based on the comparison between both locations, this study also provides guidelines for future applications to other locations.

KEYWORDS: Offshore wind, scour, scour protection, probability of failure, reliability.

SITE LOCATION: [Geo-Database](#)

INTRODUCTION

Offshore wind energy is a vital contribution to promote a viable transition from fossil fuels to a renewable, clean, and more sustainable energy mix. With an estimated technical potential of about 192 800TWh/yr, offshore wind energy has the capacity to meet the current primary energy consumption, which is estimated to be circa 162 500 TWh/yr (Taveira-Pinto et al., 2020). Floating offshore foundations still strive to reach the same level of commercial implementation as bottom-fixed ones, of which monopiles are the most common type of foundation used. Monopiles correspond to about 81.2% of the foundations installed in European offshore wind projects to date (Wind Europe, 2021).

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In offshore wind foundations, the costs may represent about 35% of the total cost of the project (Esteban et al., 2019a). Of this percentage, a portion is related to the need of applying scour protection measures—which, even if representing a small part of the 35%, can be in the order of a million euros. Therefore, the optimization of scour protections and accurate estimations of their reliability are important contributions to improve the overall competitiveness of offshore wind energy, namely when it comes to reducing the Levelized Cost of Energy (Fazeres-Ferradosa et al., 2019).

Most scour protection applied at offshore wind monopiles are comprised rock material and consist of a filter layer covered by an armor layer, i.e., the so-called rip-rap protection. The design of rip-rap scour protection is typically made by means of semi-empirical approaches that can be further validated through physical modelling tests. In terms of the armor layer definition, the most common way to design a scour protection is to derive the median stone size (D_{50}) and associated weight that ensures a stable material under wave- and current-induced bed-shear stresses, which tend to be amplified by the foundation's presence and its interaction with the flow. To have a statically stable protection, one typically applies a stone size that has a critical shear-stress that is larger than the maximum shear stress expected at the location. For several years, the common procedure to design a static scour protection was to follow Soulsby's method (Soulsby, 1997). Alternatively, one can opt for a design where a controlled movement of the stones in the armor layer is allowed, as long as no excessive exposure of the filter layer occurs, e.g., as in De Vos et al.(2012), i.e., dynamic scour protections.

Since scour protection design has a semi-empirical nature, and, to a certain extent, uncertainty related to scour phenomena and due to the lack of long-term data from field protections, it is often difficult to have an accurate perception of the protection's reliability over their design life. Additionally, for the sake of safety, design choices commonly lead to oversized protection, which may increase the foundation costs.

In order to estimate the protection's reliability and to assess the optimization potential of the armor layer material in rip-rap protections, Fazeres-Ferradosa et al. (2018a) presented a probabilistic methodology that enables one to derive the probability of failure of an existing scour protection or to obtain the value of D_{50} for a target probability of failure (considered by the designer as the acceptable one). This methodology was developed for both static and dynamic scour protections using the case study of the Horns Rev 3 offshore wind farm. The results of such research indicated that for the same level of safety, a static scour protection could be optimized to have a dynamically stable armor layer, resulting in a reduction of the median stone size roughly from 0.54 m to 0.26 m. Additionally, Fazeres-Ferradosa et al. concluded that between these two values, a range of D_{50} could be used and still yield low probabilities of failures (in the order of 10^{-4}).

Despite the usefulness and promising results of this probabilistic methodology for the Horns Rev 3 case, a key shortcoming is that it is still lacking the application to other offshore wind farms. Hence, the subsequent research and conclusions derived from e.g., Fazeres-Ferradosa et al. (2018c, 2019) still require validation for a broad range of offshore wind farms. Extending this methodology to other cases would enable a deeper discussion on what is the expected order of magnitude of the probabilities of failure for rip-rap scour protections, and also a better understanding of which probability of failure could be considered as acceptable for design purposes.

With the aim of filling in this knowledge gap, the present work extends the probabilistic assessment of Fazeres-Ferradosa et al. (2018a) to the case study of the Egmond aan Zee offshore wind farm, and compares it with the available results for Horns Rev 3. Additionally, given the lack of guidelines and standards to perform the probabilistic assessment and design of scour protections, this work provides recommendations for future case studies.

CASE STUDIES

Horns Rev 3 Offshore Wind Farm

Horns Rev 3 is located in the Danish sector of the North Sea (Figure 1, on the left), and is roughly between 20 - 30 km north-west of Blåvands Huk and 45 - 60 km from Esbjerg. This location is characterized by shallow water depths ranging from 10 - 20 m, and the local seabed is mostly comprised of non-cohesive sands. This offshore wind farm comprises 49 wind turbines with scour-protected monopile foundations. Full details on this case study and associated references are described in Fazeres-Ferradosa et al. (2018a). The hindcast metocean data used for this case study corresponds to the coordinates latitude of 55.725°N and longitude of 7.750°E and includes a time-series of significant wave heights (H_s) and peak periods (T_p) with 90 553 pairs, with an hourly resolution for the period of 01-01-2003 to 01-05-2013. For the present case study, a water depth of 18 m was assumed as in Fazeres-Ferradosa et al. (2018a).

Egmond aan Zee Offshore Wind Farm

Egmond aan Zee is located 10 - 18 km off the Dutch North Sea Coast and comprises 36 wind turbines with scour protected monopile foundations (Figure 1, on the right). The selected hindcast data corresponds to the coordinates latitude of 52.606°N and longitude of 4.419°E. The hindcast data for this case study was obtained from CMEMS hindcast data and has a temporal resolution of 3 hours. The available time-series covered the period between 01-01-1980 to 31-08-2021, which resulted in 117120 pairs of significant height and joint peak periods. The water depth was assumed as 20 m and the remaining details for this case study are provided in Figueiredo et al. (2022).



Figure 1. Location of the Egmond aan Zee (on the left) and Horns Rev 3 (on the right) offshore wind farms.

METHODS

Statistical Models for Wave Data

In order to estimate the probabilities of failure of each scour protection, the wave data requires the fitting of one or more statistical models. These enable the assessment of the joint metocean conditions at the offshore wind farms' locations, which in turn provide the combined significant wave height and peak periods that serve as inputs to calculate the probability of failure. In the present case, a Conditional Modelling Approach as recommended in DNV-RP-C205 and DNV-CN30.6 was implemented.

As discussed in Vanem et al. (2019), these recommended models may not always lead to the most accurate fitting to the local data, namely, in shallow water locations highly influenced by the local bathymetry. In this case, the shallow water effects have different impacts on each location's modelling, since between both locations such effects are non-linear. Nevertheless, the same model is used for both locations since the analysis of the water depth influence is outside the scope of the present work. Future studies on these locations and a proper modelling of the shallow water effects on the simulations of the wave's characteristics could lead to more accurate results of the probabilities of failure; e.g., a potential solution would be the use of the model developed in Vanem and Fazeris (2022).

The conditional modelling approach provides the joint distribution of the two variables and is estimated by assuming that the marginal distribution of the significant wave height is a 3-parameter Weibull distribution, and the marginal distribution of the peak period is a lognormal distribution with location and scale parameters conditioned on the value of the significant wave height (Bitner-Gregersen, 2015).

Figure 2 shows the conditional model applied to both Horns Rev 3 (red-left) and Egmond aan Zee (green-right). Horns Rev 3 data modelling is also provided in detail in Fazeris-Ferradosa et al. (2018a). It is seen that the models generally tend to fit the available time-series reasonably well.

The procedures applied to treat the data for time-dependency and seasonal variability are the same as the ones detailed in Fazeres-Ferradosa et al. (2018b), and lead to simulated pairs of H_s and T_p that correspond to maximum weekly values. As mentioned, the conditional model provides the joint H_s and T_p pairs used to estimate the damage number in the following sections. Here the water depth has been modelled as a Gaussian distribution (see Fazeres-Ferradosa et al., 2018), and the generated wave heights are limited by a ratio of wave height to the water depth of 0.6. This is made to comply with the wave breaking limits, as suggested in Fazeres-Ferradosa et al. (2019).

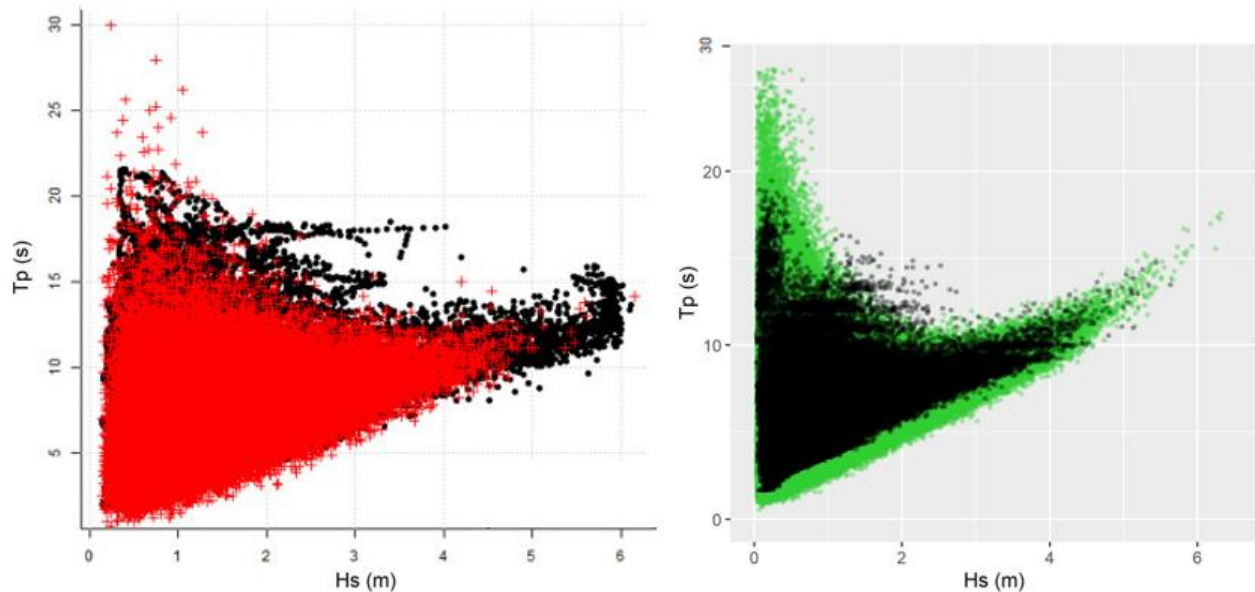


Figure 2. Conditional Model applied to Horns Rev 3 (left, in red) and Egmond aan Zee (right, in green) hindcast data. Samples of 50,000 H_s and T_p pairs are plotted as an example.

Both locations tend to show maximum significant wave heights in the order of 6 m and maximum peak periods above 20 s. Some overprediction of peak periods seems to occur, around 25 - 30 s. However, these are associated with small values of significant wave height and thus do not tend to cause failure of the scour protection applied in both cases. Therefore, their impact on the probability of failure is also expected to be rather small. Once again, these prediction “artifacts” can, to some extent, be avoided with more accurate models, such as the aforementioned Vanem and Fazeres-Ferradosa (2022).

Definition of Failure in Monopile Scour Protections

As described in De Vos et al. (2012), dynamic scour protections are feasible for monopile foundations if the damage number does not exceed the value of 1, which was observed through the physical modelling campaign that it is associated with an area of filter exposure in the order of $4(D_{n50})^2$. A discussion of this value and its relationship with the scour protection thickness has been discussed in Fazeres-Ferradosa et al. (2018c). As an example, $S_{3D}=1$ means that a scour depth $1 \times D_{n50}$ has occurred over a horizontal area of 2 by 2 stones with a size of D_{n50} each; i.e., an area of $4(D_{n50})^2$ is showing the removal of one layer of armor stones. Thicker armor layers may withstand larger damage numbers; however, for the sake of comparison, in this case the unitary value is assumed for both offshore wind farms.

Considering a dynamic stability design criterion, the armor stones are allowed to move to some extent. This approach contrasts with static scour protection in which the armor layer stones are not allowed to move for a given design condition. As a result, its application generally leads to reduced stone sizes (Fazeres-Ferradosa et al., 2018a). The approach proposed by De Vos et al. (2012) is adopted and the predicted damage number (S_{3D}) is given by:

$$S_{3D} = N_w^{b_0} \times \left(a_0 \frac{U_m^3 T_{m-1,0}^2}{\sqrt{gd}(s-1)^{3/2} D_{n50}^2} + a_1 \left(a_2 + a_3 \frac{\left(\frac{U_c}{w_s} \right)^2 (|U_c| + a_4 U_m)^2 \sqrt{d}}{g D_{n50}^{3/2}} \right) \right) \quad (1)$$



where N_w is the number of waves in a reference storm, d is the water depth (m), U_c is the depth-averaged current velocity (m/s), U_m is the bottom orbital velocity (m/s), s is the relative density of the stones, and w_s is the rock settling velocity (m/s) based on the median stone size. D_{n50} is the nominal median stone diameter (m), equal to $0.84D_{50}$. The parameters b_0 , a_0 , a_2 , and a_3 are equal to 0.243, 0.00076, -0.022, and 0.0079, respectively. The parameter a_1 takes the value of 0 for $U_c/\sqrt{gD_{n50}} < 0.92$ and waves following current, and 1 for $U_c/\sqrt{gD_{n50}} \geq 0.92$ or waves opposing current; a_4 is equal to 1 for waves following current, and $Ur/6.4$ for wave opposing current, where Ur is the Ursell number.

In this study, a number of waves N_w of 3,000 is considered, while the values of d and U_c for the case study of Egmond aan Zee location are provided in Esteban et al. (2019b) and used, respectively 20 m and 0.6 m/s. The bottom orbital velocity is computed according to Wiberg and Sherwood (2008). For Horns Rev 3, the reference values can be seen in Fazerer-Ferradosa et al. (2018a). In this case, one has a depth-averaged current velocity of 0.4 m/s and a water depth of 18 m. The rock density was assumed as 2,650 kg/m³ for Horns Rev 3 (as in Fazerer-Ferradosa et al., 2018a) and 2,800 kg/m³ for Egmond aan Zee (as in Esteban et al., 2019). These values are summarized in Table 1, as follows:

Table 1. Description (ISSMGE International Journal of Geoengineering Case Histories).

Reference conditions	Egmond aan Zee	Horns Rev 3
Source	Esteban et al. (2019)	Fazerer-Ferradosa et al. (2018a)
N_w (waves)	3,000	3,000
U_c (m/s)	0.6	0.4
Water depth (m)	20	18
ρ_{armour} (kg/m ³)	2,800	2,600

Probability of Failure in Dynamic Scour Protections

The detailed framework for probabilistic assessment is provided in Fazerer-Ferradosa et al. (2018a). In summary, the present method consists of Monte-Carlo based simulations, which are carried out to simulate pairs of H_s and T_p , that are used to simulate the protection's response in terms of S_{3D} . In the present case, the number of simulations was defined based on DNV's recommendations (DNV, 1992), which recommends a minimum number of samples equal to $100/AP_f$, where AP_f is the annual probability of failure.

DNV (1992) indicates acceptable annual probabilities of failure of marine structures depending on their class of failure, which considers the possibility for timely warning of failure and the consequences of failure in terms of loss of life. However, as noted by Fazerer-Ferradosa et al. (2018a), guidelines on the acceptable values of probability of failure are not available in the specific case of scour protection for offshore wind structures. Nonetheless, given that risk to life upon failure can be considered small for unmanned offshore wind foundations, values of AP_f between 10^{-3} and 10^{-4} could be considered a reasonable assumption, at least for the sake of comparison of the locations herein studied. This leads to an interval of a minimum number of simulations that stays between 100,000 and 1,000,000.

Fazerer-Ferradosa et al. (2018a and 2019) conducted two studies for Horns Rev 3, where the probability of failure for dynamic scour protections was shown to be reasonably stable after 200,000 simulations, with the study performing up to 1,000,000 simulations of H_s and T_p . It is important to note that in the present work, the simulated values correspond to a space of all possible occurrences of H_s and T_p at each location based on the available data sets. The number of simulated pairs does not entirely relate to a specific return period (T_r) used in the actual design of these scour protections. Despite the fact that one may calculate the correspondent pair associated to $T_r=50$ years by fitting a joint cumulative distribution function to the simulated values, the interest of this paper is to compare both case studies, and such comparison has been done for the same number of simulated values.

In the present case, since the original data available for Horns Rev 3 had an hourly resolution and the data available for Egmond aan Zee had a 3-hours resolution, it is not simple to directly obtain the annual probability of failure. The influence of the temporal resolution in the probabilities of failures and their annual values was not analyzed in the present study and remains a source of uncertainty that requires further study. However, as mentioned before, in both cases the maximum of



each pair corresponded to maximum weekly values of H_s and T_p . This resulted in probabilities of failure calculated for a minimum set of 1,000,000 pairs treated for time and seasonal dependence for both offshore wind farms. Also, the length of data available for both locations had an influence in the results; since simulating 1,000,000 pairs of H_s and T_p with 10 years (Horns Rev 3) or 41 years (Egmond aan Zee), the probabilities of failure obtained with less data have a larger uncertainty than the ones calculated with long data series.

For each case study, and with a reference value of a median stone diameter D_{50} , the probability of failure can then be estimated as (e.g., Puertos del Estado, 2002):

$$P_f = 1 - \exp \left(- \frac{\#(S_{3D} \geq 1)}{N_r} \right) \quad (2)$$

for the case of the simulations based on the original data. The annual probability of failure is given by:

$$AP_f = 1 - \exp \left(- \frac{\#(S_{3D} \geq 1)}{N_y} \right) \quad (3)$$

for the case of the simulations based on the pre-processed data. The $\#(S_{3D} \geq 1)$ expresses the number of cases where the scour protection is considered to fail, N_r is the total number of simulations, and N_y is the number of simulated years. In the present study, for the sake of comparison, only the values concerning Equation 3 are presented.

RESULTS AND DISCUSSION

Despite the uncertainty that arises from the application of different hindcast models, including different temporal and spatial resolution (which is addressed in Figueiredo et al., 2022), the main goal was to compare two different offshore wind farms in terms of their probabilities of failure. The intention was to understand if P_f stays within the same order of magnitude, or if its variability is significant from case study to case study. Figure 3 provides the probabilities of failure for both locations.

It is possible to see, for the same D_{50} , that between both case studies the probability of failure may vary considerably. For example, in the case of $D_{50}=0.30$ m, P_f varies up to two orders of magnitude, i.e., from 2.95×10^{-4} for Horns Rev 3 to 4.8×10^{-6} in the Egmond aan Zee offshore wind farm. In the latter case, median stone sizes above 0.38 m indicated a virtually null probability of failure, hence these have not been represented in the green curve.

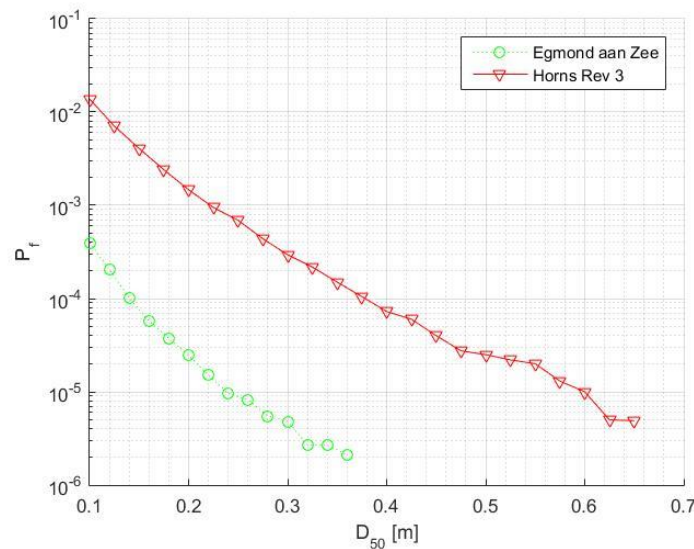


Figure 3. Comparison of the probabilities of failure for both locations, considering a dynamic stability criterion.

According to Fazeres-Ferradosa et al. (2018a) and Esteban et al. (2019b), the scour protection at both locations were designed following a static design criterion (no movement of the stones was allowed). Such design corresponded to $D_{50\text{HornsRev3}}=0.35$



m and $D_{50\text{Egmond aan Zee}}=0.4$ m. The differences in design D_{50} may not only arise from the hydrodynamic and other local conditions, but also from different return periods assumed for the local currents, typically combined with 50 years for wave heights and periods. No information was found by the authors on the actual design return periods being used in both cases. Nevertheless, results show that there is a probability for a filter layer exposure, which is in the order of 10^{-4} for Horns Rev 3. In the case of Egmond aan Zee, the likelihood of failure is virtually non-existent. The practical implication of this is that the probability of generalized failure of the scour protection is rather low, given the fact that the probability of failure for dynamic stability status is also small (e.g., around 10^{-4} or less). Therefore, even if movement occurs at the armor layer, meaning that the static stability is not ensured, the probability of reaching an exposure of the filter layer above $4(D_{n50})^2$ remains small.

Results indicate that Egmond aan Zee could in fact support a considerable reduction of its D_{50} , for example down to 0.24 m. Note that for $D_{50}=0.24$ m, the probability of failure remains in the order of 10^{-6} , which is a rather small value when compared to the other cases reported in the literature, e.g., Fazerer-Ferradosa et al. (2018a or 2019). In the case of Horns Rev 3, the D_{50} could also, to a certain extent, be optimized depending on what the designer considers an acceptable value for the probability of failure. For example, one could consider reducing the D_{50} down to 0.30 m.

Concerning the acceptable probability of failure, a thorough discussion is made in Fazerer-Ferradosa et al. (2018a, 2019) stating that P_f in the order of 10^{-4} could be considered as a reference value for probabilistic design and reliability assessment purposes. Despite the fact that this is a matter that requires further investigation applied to a broader range of case studies, the results show that Egmond aan Zee has even lower values of the probability of failure than the ones reported in the previous studies. The field studies of Raaijmakers et al. (2008, 2010) and Peterson (2014), reported scour occurrence in some of the offshore monopile foundations up to 2,500 days after the foundations' installation. However, the maximum scour depth of about $0.6D_p$ was caused by edge scour phenomena, which then led to a decrease in the protection's extent. The formulation developed for dynamic stability by De Vos et al. (2012) does not account for such a failure mode. Hence, there is no direct relationship with the failure analysis hereby provided and values reported from field campaigns.

The fact that the median stone size at Egmond aan Zee could be reduced based on the results from Figure 2, relative to the erosion of the armor layer, could contribute to a decrease in the reported edge scour severity, since smaller armor stone sizes can be related to smaller changes in the seabed roughness. Additionally, the reduction of the median stone size might lead to the reduction of the protection's thickness, which also may contribute to reduce edge scour. To the authors' knowledge, no field surveys have been reported for the scour protections at the Horns Rev 3 offshore wind farm.

The results obtained in the present case study show that the probabilities of failure of a scour protection in monopile foundations depend considerably on the site-specific conditions for each offshore windfarm. This is evident due to the large differences noted between both locations studied herein. Nevertheless, the probabilistic assessment enables one to understand the margin for further D_{50} optimizations (reductions) without having unacceptable impacts on the protection's reliability.

CONCLUSIONS

The present study extended the reliability analysis developed in Fazerer-Ferradosa et al. (2018a) to the Egmond aan Zee offshore windfarm and provided a first comparison with the previously reported case concerning the Horns Rev 3 location. The key goal of this research was to understand if the probabilities of failure of a scour protection can register considerable variations from case study to case study.

For the failure mode concerning erosion of the armor layer, it was analytically proven that the probability of failure of scour protections can vary considerably from case to case. In this case, a comparison between Horns Rev 3 and Egmond aan Zee showed that the probability of failure may vary by up to two orders of magnitude for the same D_{50} , meaning that such measure of the protection's reliability can be very site-specific.

Regardless of these differences and considering the median stone sizes applied in both locations, it was shown that the probability of failure had reasonably low values, e.g., in the order of 10^{-4} or below. Both cases consist of scour protection that was designed to be statically stable. Therefore, the analysis performed under the dynamic stability criterion indicated that the scour protection could eventually be optimized to use smaller median stone sizes.

The results showed that further research is required: specifically, by extending this analysis to other case studies, in order to improve current knowledge on the failure mechanisms, likelihood, and reliability of scour protection applied to offshore wind monopile foundations. The present study has several limitations that arise from a broad range of uncertainties and



shortcomings associated with the methodologies presented in this paper. These are discussed and analyzed in the literature, e.g., Fazerer-Ferradosa et al. (2018a and 20119). Furthermore, the present paper addresses the failure mode related to the erosion of the armor layer, although other failure modes in the armor, filter, or outer edges of the protection may occur. Future developments are required to properly estimate the reliability of these protections under multiple failure mechanisms. The following recommendations can be provided for future design operations based or partially supported on a probabilistic assessment:

- Probabilistic assessment and design of scour protection can lead to probabilities of failure and associated D_{50} values that vary significantly from one case to another. Thus, it is crucial to avoid generalizations of suitable values of P_f between windfarms at different locations.
- The literature has very few reported cases of probabilistic analyses of scour protection and no general guidelines are available for all cases. Nevertheless, $P_f < 10^{-4}$ seems to be a reasonable reference value for this type of rip-rap structure.
- If a dynamic design is to be performed, it is recommended that the P_f vs D_{50} curve is plotted to understand how the reduction to a smaller D_{50} impacts the probability of failure of the scour protection.
- If possible, as performed in Fazerer-Ferradosa et al. (2018a), the P_f vs D_{50} curve should be plotted for both the static and dynamic design criteria, e.g., based on Soulsby (1997) or De Vos et al. (2012).
- Given the large variances in P_f , it is advisable to perform sensitivity analyses, as the ones presented in Fazerer-Ferradosa et al. (2018a or 2019) for a better perception of the protection's reliability behavior.

The probabilistic analysis of scour protection requires further development and application to other case studies, and this remains a key step. However, it is recommended, as a preliminary approach, to check for potential reductions of D_{50} starting from the statically stable value to a dynamically stable one. Such reductions or optimizations should always be validated by means of physical modelling tests as a standard procedure.

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Appendix II – Chambel *et al.* (2024)



Research paper

A comprehensive review on scour and scour protections for complex bottom-fixed offshore and marine renewable energy foundations

J. Chambel^{a,b,*}, T. Fazerres-Ferradosa^{a,b}, F. Miranda^{a,b}, A.M. Bento^{a,b}, F. Taveira-Pinto^{a,b}, P. Lomonaco^c

^a Hydraulics, Water Resources, And Environmental Division, Department of Civil Engineering, Faculty of Engineering of the University of Porto, 4200-465 Porto, Portugal

^b Interdisciplinary Centre of Marine and Environmental Research of the University of Porto (CIIMAR), 4450-208 Matosinhos, Portugal

^c O.H Hinsdale Wave Research Laboratory, College of Engineering, Oregon State University, Corvallis, OR, United States

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Hybrid foundations

ABSTRACT

Due to the marine environment's complexity, optimising offshore foundations' design is still a major focus of the scientific and industrial community, since foundations represent a large portion of the total investment. Scour is one of the main causes that lead to ultimate, and service limit states, impacting design optimization and costs. Scour at monopile foundations has been extensively studied. However, advances in scour protections for hybrid structures, and other bottom-fixed foundations for offshore renewable energy harvesting technologies are often kept confidential by stakeholders, and knowledge gaps must be covered. Thus, the present paper provides a summary of the most recent physical and numerical studies related to scour and riprap scour protections for complex bottom-fixed foundations, such as jackets, tripods, gravity-based foundations (GBF), high-rise structure foundations (HRSF), and suction buckets, while covering other marine energy harvesting technologies as well, including wave energy converters (WEC) and tidal energy converters (TEC). This manuscript presents knowledge gaps, recent improvements, and potential studies on hybrid foundations – offshore wind turbine foundations combined with WECs or TECs. It is shown that offshore scour protection is a study field with a wide margin of development, but crucial for the future of the offshore renewable energy sector, thus pointing out key challenges and major opportunities for future research.

1. Introduction

As one of the most attractive forms of clean energy, the offshore wind energy sector (OWS) has been seen as an important part of the future of renewables and energy transition, particularly given the European efforts and policies towards net-zero carbon emissions, to be achieved by 2050 (WindEurope, 2021a). OWS has experienced an increase in demand due to the expansion and competitiveness of the sector, with more efficient and mature technology, and a continuous reduction of the Levelized Cost of Energy (LCoE).

In bottom-fixed Offshore Wind (OW), the foundation is typically responsible for around 30% of the overall investment (Matutano et al., 2013; Bhattacharya, 2014), and an essential part of that investment is allocated to scour protection (Fazerres-Ferradosa et al., 2019a). Due to the complexity of the offshore environment, understanding the impact that entails the foundation and protection design is vital for design optimization purposes of those two structural components, causing a

positive impact on the decrease of global investment and the LCoE. Scour protections are one of the preferential contributors to achieving a cost reduction given the empirical nature of its design. Over the past decade, scour protection solutions have registered major advances, and could potentially be applied to complex foundations, wave/tidal energy converters, and eventually offshore hybrid foundations as well (Fazerres-Ferradosa et al., 2021).

It is expected that by 2030, bottom-fixed and floating offshore wind turbines will experience an LCoE reduction of 44%–48 €/MWh and 65% to 69 €/MWh, respectively, when compared to 2020, far less from the 150 €/MWh value of the 2010s (WindEurope, 2021a, 2022a). To reach climate neutrality, wind energy needs to cover 25% of European Union (EU) demands by 2030 and 50% by 2050 (17% of them being OWS) with 81% renewables (WindEurope, 2021a). In the short period, it will be necessary for a total wind energy capacity of 453 GW–79 GW of OWS (WindEurope, 2022b). To attain that mark is imperative to install, between 2022 and 2026, at least 27.9 GW of offshore wind, nearly 8.5

* Corresponding author.

E-mail address: up201304674@fe.up.pt (J. Chambel).

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GW/year – significantly different from the 3.4 GW installed in 2021 (WindEurope, 2022b).

The implementation of some of the developments and novel design methods for scour protections is kept private by most of the industrial stakeholders. However, some topics need to be addressed, that can have a major influence on optimized designs, such as the scour patterns and scour protections for complex foundations and new geometries; the impact that WECs or TECs produce on the flow field, seabed, and protections; effects that offshore wind turbine lifetime cycle extension can cause on existing foundations; or effects that repowering or more powerful turbines can or should have on the dimensions of the foundations and consequently in the design of the scour protections (Fazeres-Ferradosa et al., 2021).

The challenges, trends, and knowledge gaps regarding offshore scour protections and foundations ask for an uninterrupted research effort by the scientific community. Therefore, this article presents a review of the latest outcomes of scour protections applied in complex bottom-fixed structures for offshore wind and marine energy harvesting technologies. It aims to encapsulate the existing knowledge and most recent research performed on offshore foundations' scour protection, from monopiles to more complex and hybrid foundations, and point out potential research fields and synergies.

The paper is organized as follows: Section 2 briefly references the most recent design methodologies and optimizations of scour protections. Section 3 provides a broad review of the latest findings in scour and scour protections for complex structures (jackets, tripods, and GBFs), referencing different physical and numerical model studies. Section 4 gives a general insight into marine energy harvesting technologies such as wave energy converters, tidal energy converters, and hybrid foundations. Finally, in Section 5, some conclusions, knowledge gaps, and future research lines are highlighted.

2. Offshore scour protection design methodologies

Offshore structures are used for multiple purposes. Some of them are implemented in fixed platforms, others in floating platforms, such as production, storage, offloading platforms, oil/gas rigs, offshore high voltage stations (OHVS), and offshore wind turbines (OWT) – Amaechi et al. (2022) and Haritos (2007).

Regarding OWTs, their foundations can have different configurations and can be placed in a wide range of water depths, thus being divided into two major groups.

- **Bottom-fixed foundations:** foundations fixed on the seabed. Monopiles are the most used, placed mainly in shallow waters (until 30 m deep). Other, and more complex foundations, such as jackets, tripods, GBFs, and Suction Buckets are better suited for transitional waters (until 50–60 m deep) – Fig. 1. Recently, a new type of complex foundation, the High-Rise Structure Foundation (HRSF), has been

gaining some momentum and has been often used in Asian offshore wind farms - Fig. 2;

- **Floating offshore wind turbines (FOWT):** OWT with floating platforms attached to the seabed by mooring lines and anchors, including barge, semi-submersibles, Spar buoys, and tension leg platforms (TLPs).

Only 18.5% of the OWT foundations in Europe are complex bottom-fixed foundations (Fig. 3) – jackets (9.9%), GBFs (5%), tripods (2.2%), and tripile (1.4%), WindEurope (2021b).

OWT might be placed in movable seabeds with either cohesive or non-cohesive properties. The offshore conditions can vary significantly, so the structure foundations' presence induces considerable flow changes. The interactions between the flow and the structure, increase the bed shear stress, since local velocities increase, as well as flow-induced turbulence, thus initiating sediment transport. When the critical bed shear stress is exceeded, the scouring process begins (Sumer et al., 2001; De Vos et al., 2011; Whitehouse et al., 2011a; Sørensen and Ibsen, 2013). So, scour can be defined as the generalized erosion of the seabed in the structure surrounding area, as a result of the interaction between the soil, flow, and structure. It is the leading cause of structural failure by ultimate or service-limit states. Hence, scour protections play a critical role in the OWT design and overall costs. For bottom-fixed foundations, scour protections are placed around the foundation. Conversely, at FOWT scour protections should be established around elements that are more exposed to scour such as drag-embedment anchors (DEA) and their associated subsea structures such as tensioners, clump weights, and chains (Sumer and Kirca, 2022).



Fig. 2. High-Rise Structure Foundation (HRSF), Reprinted with permission from Xiao et al. (2020), Copyright 2020, Elsevier.

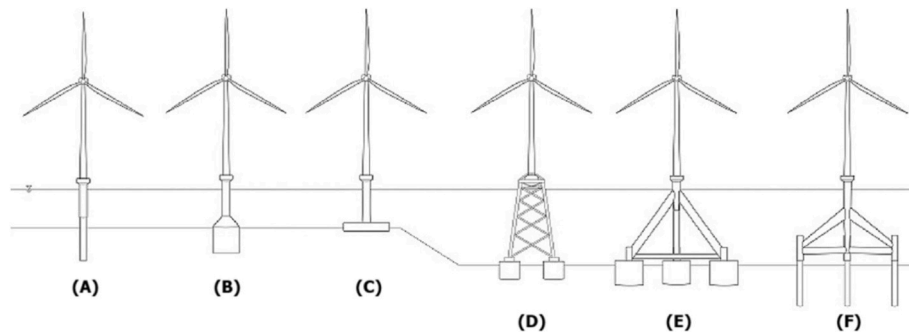


Fig. 1. Bottom-Fixed Foundations: (A) Monopile, (B) Monopile with Suction Bucket, (C) Gravity-Based Foundation, (D) Jacket with Suction Bucket, (E) Tripod with Suction Bucket, (F) Tripod – adapted from Bhattacharya (2014).

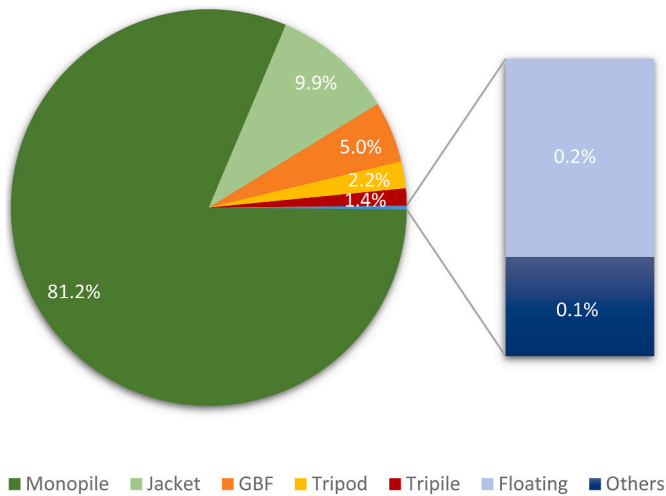


Fig. 3. – Offshore wind foundations installed in Europe by type (WindEurope, 2021b).

2.1. Scour countermeasure classification

As scour develops around the foundation, the overall structural response changes regarding the serviceability, eigenfrequency, and fatigue limit state. Scour protections must be designed to prevent erosion of the seabed sediments while preserving permeability to prevent larger pore pressure increments, allowing seepage water drainage (Saathoff et al., 2024). Moreover, scour protections can have a positive impact on the foundation's stiffness (up to a 50% increase), Saathoff et al. (2024). However, different protective measures have different costs and they are highly susceptible to location, material size, availability, transport, and installation, as well as to marine environmental conditions, including water depth, wave characteristics, current velocity and direction, wave-current interaction, tides, storm surges, and storm durations, among others (Fazeres-Ferradosa et al., 2021; Chambel, 2019). Different studies have been performed for distinct scour countermeasures (Fazeres-Ferradosa et al., 2019b; Vahdati et al., 2020; Corvaro et al., 2018). According to Li et al. (2023), Zhang et al. (2023), and Tang et al. (2022), there are two major groups of scour countermeasures.

- **Passive protections:** the most common countermeasure. Used to control or reduce scour by strengthening the seabed sediment particles or by using armouring structures around the foundation. They are known for their cost-effectiveness and ease of application. Riprap

protection and rockbags are probably the two most used solutions in offshore wind farms;

- **Active protections:** passive countermeasures require maintenance and could have a certain life span due to aggressive offshore conditions, leading to structural failure in some cases. Therefore, active countermeasures became in demand, as they intend to reduce scour by altering the flow patterns around the foundation and/or by reducing the flow intensity. Within the most known it can be highlighted systems like collars, vanes, and sacrificial piles.

Furthermore, a third classification (comprehensive protection) was introduced by Zhang et al. (2023), to categorize countermeasures that incorporate both active and passive protections or scour protections that combine or use additional biological or eco-friendly components. Fig. 4 encapsulates the overall range of possible scour mitigation measures that can be applied in the offshore, marine, and fluvial environments.

2.2. RipRap scour protections

Riprap protections, inspired by rubble-mound breakwaters, placed around the foundation (Fig. 5), are the most common solution due to their high availability and low cost (Fazeres-Ferradosa et al., 2019a; De Vos, 2008). It was demonstrated by Ma and Chen (2021) and Yin et al.

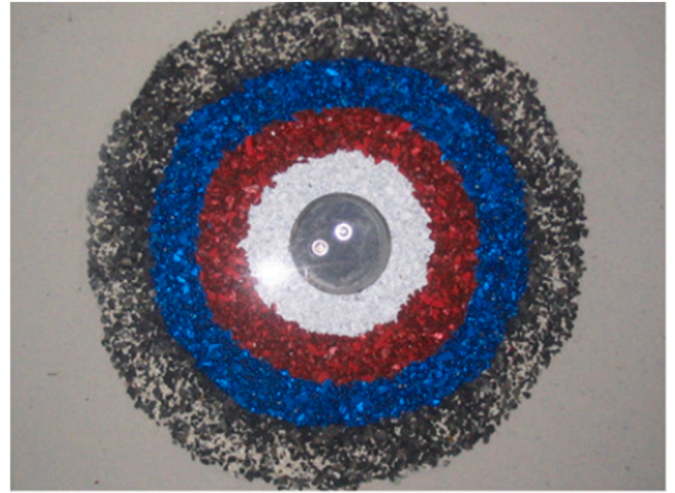


Fig. 5. Riprap scour protection model for a monopile – Adapted and Reprinted with permission from De Vos et al. (2011). Copyright 2011, Elsevier.

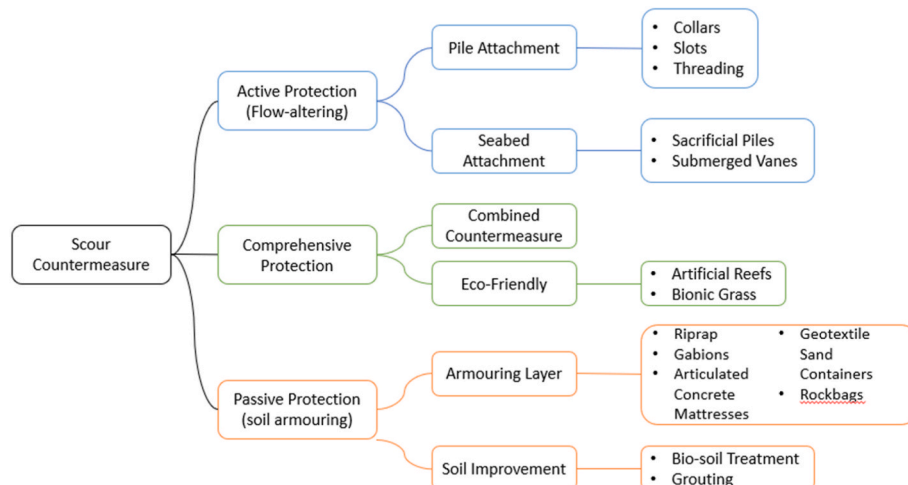


Fig. 4. Scour countermeasures classification according to Li et al. (2023), Zhang et al. (2023), and Tang et al. (2022).

(2023) that they enhance the structural behaviour of the foundation as they could decrease the cross-sectional rotation up to 18% in a service-limit state, but also improve the foundation's reliability index, thus having a positive effect on the ultimate limit state.

According to De Vos et al. (2011, 2012) and Schendel (2018), they are usually classified as follows.

- **Static protections:** the movement of the elements of the armour layer is not allowed. This is the most common type of protection used in commercial offshore wind projects (Fazeres-Ferradosa et al., 2021). The static design is based on the threshold of motion concept, which states that the critical stone size (D_{cr}) should be determined so that the shear stress induced by environmental conditions is smaller than the critical shear stress of the material (Soulsby, 1997). The most common design formula (Equation (1)) was presented in Soulsby (1997), where the mass density of the material (ρ_s) directly impacts the median stone size ($D_{50}=D_{cr}$) used – where τ_{cr} (N/m²) is the critical bed shear stress, ρ_w (kg/m³) is the water mass density, and θ_{cr} is the critical Shields parameter, which for non-cohesive soils a dimensionless grain size (D^*) larger than 100 has an asymptotic value of 0.056, Soulsby (1997).

$$\tau_{cr} = \theta_{cr} g (\rho_s - \rho_w) D_{50} \quad (1)$$

$$D^* = \left(\frac{g(s-1)}{v^2} \right)^{1/3} d_s \quad (2)$$

When applied to monopiles or other complex foundations, an amplification factor, the ratio of disturbed over undisturbed bed shear stress, is included to consider the effect that the bottom-fixed foundations produce on the increase of wave-current shear stress. For monopiles, amplification factors were studied by Whitehouse (1998) and Sumer and Fredsøe (1997). However, those amplification factor values cannot be extrapolated for complex structures. Therefore, the static design of scour protections and the adequate values of the amplification factor for complex foundations represent a considerable knowledge gap.

- **Dynamic protections:** a controlled movement of the elements of the armour layer is allowed. Although not extensively used in commercial offshore projects, or at least not publicly disclosed, they have been the scientific community's focus for the last 18 years, and represent an upgrade to static protections, in the sense that allows for a reduction of the median stone size of the armour. Design formulas have been studied and proposed by De Vos (2008) and De Vos et al. (2012). Still, the first studies mentioning dynamic protections were conceived in the OPTI-PILE project by den Boon et al. (2004), where the threshold of motion ceased to be the criteria for the design. Instead, De Vos (2008) and De Vos et al. (2012) developed a new design approach that defined failure when the filter layer is exposed in an area equivalent to $4.5D_{n50}^2$ – comparable to a square of two-by-two D_{n50} stones. A damage number (S_{3D}) equation was proposed De Vos (2008) and De Vos et al. (2012), based on the breakwaters formula of Van Der Meer (1990), Equation (3), allowing the protections' classification into three different levels of damage: static ($S_{3D} < 0.25$), dynamic ($0.25 < S_{3D} < 1.00$), and failure ($S_{3D} \geq 1.00$).

$$S_{3D} = a_0 \frac{U_m^3 T_{m-1,0}^2}{\sqrt{gd}(s-1)^{3/2} D_{n50}^2} + a_1 \left(a_2 + a_3 \frac{(U_c/w_s)^2 (U_c + a_4 U_m)^2 \sqrt{d}}{g D_{n50}^{3/2}} \right) \quad (3)$$

where N is the number of waves, g (m/s²) is the gravitational acceleration, d (m) is the water depth, U_m (m/s) is the orbital velocity, $T_{m-1,0}$ (s) is the energy wave period, s is the ratio between ρ_s and ρ_w , U_c (m/s) is the depth-average velocity, w_s (m/s) is the settling velocity, a_0 , a_2 , a_3 and b_0 are regression coefficients equal to 0.00076, −0.022, 0.0079 and 0.243, respectively, and a_1 and a_4 are coefficients for hydrodynamic conditions defined in De Vos (2008) and De Vos et al. (2012).

Opposite to the static design method, the dynamic design equation does not rely on the amplification factor. When compared to static protections, dynamic ones typically have a decreased stone size (D_{n50}) and thickness (Table 1), which is expected to lead to smaller material, transportation, and installation costs (Matutano et al., 2013). However, an excessive reduction of D_{n50} . Can still lead to thicker armour layers to sustain damage without failure, eventually increasing costs (Fazeres-Ferradosa et al., 2021). Therefore, a balanced solution is required for practical optimization. Furthermore, like static protections, most studies only considered monopile foundations and a short variety of water depths and layer thicknesses. Therefore, in the application of dynamic scour protections to complex foundations, there is a large knowledge gap yet to be fully covered.

- **Wide-graded protections:** single-layer protections formed by wide-graded material that simultaneously plays the role of armour and filter, and that can have a static or dynamic behaviour. Several researchers (Schendel, 2018; Schendel et al., 2014, 2016, 2018) performed studies and optimized this type of protection. They consensually registered an overall stability increase, when compared to narrow-graded protections. Such stability is pointed out as a result of the sheltering of smaller stones between the voids of larger ones. Wide-graded protections are almost static under currents, rather than under waves in which they tend to be dynamically stable when compared to other protections with the same D_{50} , Schendel et al. (2014). For static wide-graded protections, the design formula (Equation (4)) was presented by De Vos et al. (2011):

$$\tau_{cr} = \theta_{cr} g (\rho_s - \rho_w) D_{67.5} \quad (4)$$

where $D_{67.5}$ and $\theta_{cr} = 0.035$ are used instead of D_{50} and $\theta_{cr} = 0.056$, so the τ_{cr} for wide-graded protections will be larger than for narrow-graded protections, for the same D_{50} value (De Vos et al., 2011).

For dynamic wide-graded protections, the dynamic design formulas do not apply since they are based on a filter exposure that does not exist in wide-graded protections. They can be an appealing type of protection, from the stability, material availability, installation, and cost point of view in some cases. The literature reveals, however, a lack of dynamic design formulas specifically developed for wide-graded single-layer scour protections, both for monopiles and for complex foundations. Also, there is a lack of reported experimental data, tests, and results, as well as field applications. Thus, wide-graded protections still represent a concept whose efficiency is yet to be fully understood.

In terms of efficiency, Wang et al. (2023a) compared the scour depth obtained from an unprotected monopile to a monopile protected with riprap static and dynamic protections. The results showed a maximum scour depth reduction of 26.1% (static), 73.8% (dynamic single-layered), and 86.9% (2-layered dynamic protection), respectively. However, for clarity, the tests were performed using only steady currents. Nonetheless, the results are a good indication that not only dynamic protections can be cheaper, but they can also have higher performance on counteracting scour.

2.3. Alternative passive scour protections

Regarding other scour countermeasures, this review focuses primarily on riprap scour protections. However, a brief mention will be made of solutions with an armouring effect around the foundation. A more extensive review of other alternative protective systems can be found in Li et al. (2023), Zhang et al. (2023) and Tang et al. (2022), as they are not the focus of this review. The studies found in the literature, regarding armouring and strengthening scour mitigation systems, mention mainly partial grouting, gabions, articulated concrete mattresses (ACM), and geotextile sand containers (GSC). They are usually implemented to counter scour in bridges, river slopes, and nowadays in offshore wind farms (Li et al., 2023; Zhang et al., 2023; Tang et al.,

Table 1

- D_{50} (m) comparison of different design approaches for the same tested conditions: $d = 20$ m; $H_{m0} = 6.5$ m; $T_p = 11.2$ s; $U_c = 1.5$ m/s; $D_{85/15} = 2.5$ (prototype values) – adapted from De Vos et al. (2011), De Vos (2008), and De Vos et al. (2012).

Static Approach				Dynamic Approach		
Amplification Factor (α_f)	Fredsoe and Deigaard (1992) (use of τ_m)	Soulsby (1997) (use of τ_{max})	De Vos et al. (2011) (Equation (1))	S_{3D} (Equation (3))	De Vos (2008), De Vos et al. (2012) (Waves following Currents)	De Vos (2008), De Vos et al. (2012) (Waves opposing Currents)
2	0.68	0.66	0.496	0.2	0.44	0.46
3	1.30	1.51		0.5	0.32	0.36
4	1.97	2.75		1	0.27	0.28

2022). Recently, new eco-friendly scour protections, such as microbially induced calcium-carbonate precipitation (MICP), Li et al. (2022a, 2022b), ionic soil stabilizers (ISS), Hu et al. (2022a, b), artificial reefs (AR), and bionic grass have been receiving increased interest and relevancy by the scientific community.

- **Partial Grouting:** a method in which the armour layer units are bonded together by special mortar, filling about 50% of the voids, to produce a high-stability layer that lasts longer against scour and has sufficient permeability to avoid excess water pressure below the protection's armour (Li et al., 2023; Zhang et al., 2023; Heibaum et al., 2010). Combines a high resistance against currents and waves with the flexibility to adapt to seabed deformations. According to Heibaum et al. (2010), partial grouting protections proved stability up to flow velocities of 8 m/s in laboratory tests. Zhang et al. (2022) carried out a series of physical model tests using currents, waves, and combined waves and currents to compare an unprotected to a partial grouting monopile foundation. When comparing the grouted to the “ungrouted” model, it was concluded that the critical shear stress needed to initiate scour from the incipient motion of particles in the grouted monopile was 10 times higher when compared to the “ungrouted” monopile. Therefore, for weak hydraulic actions only the unprotected monopile had suffered from scour. However, when strong hydraulic conditions were applied, some cracks and scour holes occurred around the foundation for the grouted protection. Nonetheless, Zhang et al. (2022) concluded that grouting protections could be more efficient under extreme hydrodynamic conditions when compared to riprap protections. To study this possible enhancement, Wang et al. (2023b) performed a series of physical large-scale model tests on grouted riprap protection (Fig. 6a), where the armour layer units were cemented. By applying two extreme

wave-current conditions with return periods of 50 and 100 years, it concluded that the maximum scour depth could be reduced up to 80% when compared to an unprotected monopile;

- **Gabions:** wire sacks, boxes, baskets or mattresses filled with riprap material that are used to improve stability and reduce scour (Li et al., 2023). The gabions are predominantly used on bridges or for the stabilization of river margins as described in Pagliara et al. (2011), Singh et al. (2022), and Agrawal et al. (2007). However, no studies or *in-situ* applications regarding the use of gabions as a scour protection for OWT foundations were found in the literature;
- **Articulated Concrete Mattresses (ACM):** a matrix of concrete connected through wires to form a single protective unit, has the advantage of being manufactured before the OWT installation with rigours and higher control quality (Li et al., 2023). Although not applied directly to an OWT foundation, Coghlan et al. (2023) tested these mats under wave-induced loading for a small-scale model of the monolithic maritime structure of the Port of Hay Point (Australia) – Fig. 6b. The original mats provided seabed scour protection successfully for almost 50 years. However, the results showed that the original degraded mats had insufficient stability under extreme wave conditions, mainly at the caisson corners. Therefore, newly upgraded mats were implemented and successfully tested as new countermeasures. Liang et al. (2022) performed a three-dimensional (3D) numerical model to study the seabed instability around an offshore pipeline under multiple wave-current hydrodynamic loads, when protected by ACMs. The goal was to assess the results while varying the spacing between two consecutive protections and the interaction angle (α_{wc-mp}) – ranging between 0° (pipeline perpendicular wave-current load) and 90° (pipeline colinear to wave-current load). The results allowed to extract several conclusions: the presence of the protection led to a clear reduction in

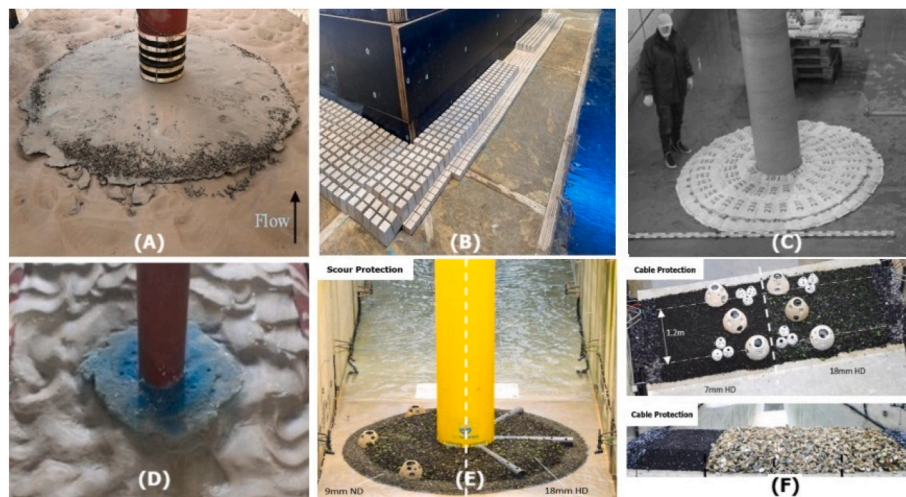


Fig. 6. Alternative scour protection systems: (A) Partial grouted riprap – Reprinted with permission from Wang et al. (2023b), Copyright 2023, Elsevier; (B) Articulated Concrete Mattress (ACM) – adapted from Coghlan et al. (2023); (C) Geotextile Sand Containers (GSC) – adapted from Grüne et al. (2006c); (D) Microbially Induced Calcium-Carbonate Precipitation (MICP) – Reprinted with permission from Li et al. (2022b), Copyright 2022, Elsevier; (E) and (F) Artificial Reefs with oysters/shells – adapted from Aleksandrova et al. (2023).

seabed sediment loss, even along the unprotected sections (around 20%); the drop of the seabed increases from the centre of the ACM protection towards its edge, where instability occurs first; the seabed loss tends to become more severe with the increase of the current velocity; when the mattress spacing exceeds 18 times the pipeline diameter, the loss of sediments in the unprotected area achieves the same range of a pipeline without any protected conditions; wave height and soil permeability were regarded as dominant factors, on behalf of the wave period and seabed saturation, in the stability design of the ACMs-pipeline system on sandy seabed's. However, [Liang et al. \(2022\)](#) suggests that the α_{wc-mp} between the ACMs-pipeline system and the hydrodynamic conditions should be the first factor considered, as the spatial distribution of the seabed sediment loss is considerable when $\alpha_{wc-mp} < 45^\circ$;

- **Geotextile Sand Containers (GSC):** GSCs or geotextiles have been massively used in geotechnical engineering and for coastal protection. Nowadays, some offshore wind farms like the OWP Amrum-bank West (Germany) opt for this type of solution as a scour protection ([Hoyme et al., 2018](#)). [Grüne et al. \(2006a, b\)](#) proposed GSCs as scour protections for monopiles, to minimize the risk of damage to the offshore foundation and the cables during the construction period. The physical model program started to investigate the GSCs' stability to inline and transverse wave-induced currents, by testing 4 GSC sizes for 3 percentages of filling, resulting in 12 different container weights. The results showed that the stability of the containers is not just a function of the total weight, but also the wave directions and percentage of filling. The experimental data have shown that increasing the percentage of filling resulted in increasing stability, i.e., GSCs with lower weight and higher percentage of filling are more stable than GSCs with higher weight and low percentages of filling. The decrease in stability was attributed to the increasing acting forces from the hydrodynamic loads because of the successive changes in the shape of the container due to the interior movement of the sand particles. As a follow-up, [Grüne et al. \(2006c\)](#) performed a large-scale model of complete scour protections around a monopile ([Fig. 6c](#)), by comparing two GSCs' placement configurations (regular and irregular). After different test series of 2000–3000 waves, in which the wave height and peak period were increased stepwise, displacements above 5% were registered for the maximum significant wave height (1.0 m). The main results indicate that no significant differences were found in terms of stability, considering both configurations of the scour protection. For irregularly placed GSCs, at the beginning, a self-adjustment process of the protection occurs. However, when the displacement of the containers starts, the process continues to occur much faster for "regular" scour protection compared to "irregular" scour protection. [Corvaro et al. \(2018\)](#) carried out experimental tests with regular and irregular waves to assess the performance of scour protections made of 80%-filled GSCs around a monopile. Several configurations (circular, two configurations with different orientations of the containers, and random) were tested and compared to an unprotected monopile. [Corvaro et al. \(2018\)](#) mentions that GSC scour protections have two major failure modes, sliding and overturning, being the second mode the main mechanism. The results showed that, generally, damage for regular waves achieved an equilibrium stage for 500 waves, while for irregular waves that condition was obtained for 1500 waves. Moreover, the squared configuration presented the best (long edge following the wave direction) and worst result (long edge transversal to wave direction) in terms of efficiency, thus showing that the wave direction has a strong influence on the protection's performance. Additionally, for the random configuration significant displacements were observed at the beginning due to the initial random arrangement to a more stable position. Hence, [Corvaro et al. \(2018\)](#) concluded that GSC scour protections reduce massively scour depths, as no failure, scour, or significative sinking/overturning was observed even for waves with large heights and peak periods, and

that the circular configuration represents the best overall solution. As a novel contribution, it developed and presented a new dynamic design formula, Equation (5a), for the determination of the container's weight based on an adaptation of the stability number (N_s) of [Hudson \(1959\)](#):

$$N_s^* = N_s \cdot k_1 \cdot \frac{H}{d} = \frac{H^2}{\Delta \cdot l} \cdot k_1 \quad (5a)$$

$$l = \left(\frac{W}{k_w \gamma} \right)^{1/3} \quad (5b)$$

being N_s $\times$ the modified stability number, $k_1 = 2kd/\sinh(2kd)$ the velocity correction factor, H (m) the wave height, k the wave number, $\Delta = (\frac{\rho}{\rho_w} - 1)$ the buoyant density of the GSC, ρ (kg/m^3) the mass density of the GSC, l (m) the length of the GSC, W (N) the weight of the GSC, k_w the GSC volume factor ($k_w = V/l^3$), γ (N/m^3) the GSC specific weight, and V (m^3) the volume of the GSC. The author then established 4 damage levels, in an analogy to the damage levels of [De Vos et al. \(2012\)](#) – no movement (Damage 0), small movement of the GSCs closest to the monopile (Damage 1), relevant movement of GSCs in the protection's total area (Damage 2), large number of GSCs closest to the monopile removed (Damage 3/Failure). By analysing the values obtained for N_s^* , and by comparing them to the visual damage levels defined, [Corvaro et al. \(2018\)](#) reported that GSCs are stable for $N_s^* < 1.2$, which corresponds to the Damage 0. Supposing that larger damage levels could be obtained, it suggested that an acceptable $N_s \times$ value for the design of GSCs characteristics (W and/or l) could be 1.5 – value corresponding to Damage 1. [Wang et al. \(2023a\)](#) also tested circle and square-shaped mattresses for monopiles. Mild scour damage was detected at the corners of the squared configuration. However, despite the effective behaviour that the geotextile appears to have on scour, [Wang et al. \(2023a\)](#) also highlights potential negative impacts on the marine environment and species;

- **Microbially Induced Calcium-Carbonate Precipitation (MICP) and Ionic Soil Stabilizers (ISS):** these relatively new and eco-friendly techniques are based on biological processes for soil improvement. It involves the formation of calcium carbonate (CaCO_3), for MICP solutions, or the mixture of cations Ca^{2+} , Mg^{2+} , and Na^+ , with anions NO_3^- and SO_4^{2-} , for ISS solutions, by forming a binder with the soil sediments, thus increasing strength and the seabed's resistance to scour ([Zhang et al., 2023](#)). According to [Li et al. \(2022b\)](#), MICP has been used for soil stabilization for over two decades. [Li et al. \(2022a\)](#) used MICP to investigate the wave erosion resistance of sandy slopes. The results showed that after two MICP treatments, the resistance of the slope was not improved, as the cementation solution permeated into the bottom. However, after four treatments, the slope's permeability decreased, the cementation remained on the top layer of the slope, and the topography remained unaffected by the wave conditions. So, as a scour protection around a monopile, [Li et al. \(2022b\)](#) used this method to assess its resistance under current-only conditions ([Fig. 6d](#)). It concluded that the maximum S/D was reduced up to 84% after only two treatments. When using four treatments, no scour was detected in the vicinity of the foundation, as the calcium carbonate crystals increased the cohesion and coating of the sediment particles. It also noted that, as scour decreased due to the cementation effect, depositions at the downstream side of the foundation disappeared but edge scour depth/length increased. The author reflects on the necessity to reflect and consider a balance between MICP protection and edge scour. Moreover, it proposed an equation that relates the S/D and the protective strength ratio (R) – quotient between the penetration resistance of the MICP-protected position and the unprotected position:

$$S/D = 0.055 + 1.62 \times 0.67^R \quad (6)$$

As for ISS solutions, they are usually applied for silts, silty clays, or sandy silt soils, forming a solidified slurry. [Hu et al. \(2022a\)](#) compared the scour of an unprotected monopile to a monopile with an ISS scour protection under currents-only and combined waves and currents. The ISS was applied with a dispersion resistance agent, silt, and distilled water (3 different mixture ratios). The results showed that the use of ISS was extremely efficient by enhancing the soil's critical shear stress, leading to a reduction of the relative scour depth (S/D) in the range of 90%–95% when compared to the unprotected monopile. [Hu et al. \(2022a\)](#) also points out the fact that scour evolution curves plotted for the cases when ISS was used, showed less fluctuation and a smaller value for the time scale period of the scour process (T_c). That was pointed out as an indicator that fewer ripples emerged around the foundation, that the equilibrium scour is achieved faster, and that the incipient motion of the sediments could be more difficult under the same hydrodynamic conditions. [Hu et al. \(2022b\)](#) used a similar approach to assess scour in a pipeline under regular waves and combined waves and currents. The results also show that ISS could prevent scour by decreasing the soil porosity and by enhancing the necessary critical shear stress for initial sediment motion. Overall, a S/D reduction between 70% to almost 100%, in some cases, was obtained when comparing a protected to an unprotected pipeline. However, [Hu et al. \(2022b\)](#) highlights two potential problems. The use of ISSs on soils where a non-cohesive layer exists underneath the solidified ISS layer could result in accumulated liquefaction as the solidified layer will prevent the dissipation of pore pressure. Besides, it also mentions that pouring ISS-solidified slurries in scour pits in the ocean environment could damage the habitats of benthic fauna that need soft soil to hide from predators.

- **Artificial Reefs (AR):** this scour protection has previously been demonstrated to effectively reduce wave-current energy, block sediments, and prevent erosion on shorelines or when combined with breakwaters while increasing biodiversity ([Srisuwan and Rattana-manee, 2015](#); [López et al., 2016](#); [Marin-Díaz et al., 2021](#); [Kim et al., 2021, 2022](#)). However, relative to their use and performance in OWT foundations, [Zhao et al. \(2023\)](#) concluded that there is a lack of research on the topic. Therefore, a 3D numerical model was built by [Zhao et al. \(2023\)](#) to study the effect of ARs on flow characteristics and scour under steady flow around an OWT. Multiple arrangements were used to assess and compare the best spacing, the best protection performance, and the best efficiency for maximum scour depth. Based on the results, it was possible to conclude that ARs reduce scour by 20%–30%, depending on the arrangement (single, parallel, tandem or stack ARs) and distance from the OWT foundation. [Aleksandrova et al. \(2023\)](#) performed large-scale wave-only tests (scale factor 1:6) and small-scale wave-current tests (scale factor 1:30) on multiple eco-friendly scour protection layouts for monopiles ([Fig. 6e](#)) and cables ([Fig. 6f](#)), by integrating artificial reefs (reef balls and holey pipes), oysters and loose shells on a double-graded riprap scour protection. The aim was to assess the effect of edge scour on the stability of those eco-friendly elements. The test results have shown that the AR structures when compared to a control case (monopile only with scour protection), did not induce extra deformations. The deformation pattern is shifted depending on the placement of the structures. Therefore, ARs may have some influence on the deformation patterns. Moreover, they tend to become unstable under severe hydrodynamic loading, mainly when placed inside the monopile amplification zone (radius equal to 3 times the pile diameter). That may cause collisions and damage to the surrounding infrastructure. [Aleksandrova et al. \(2023\)](#) highlights the importance of avoiding areas of the scour protection where significant flow amplifications and large reshaping of the armour layer may occur. For the holey pipes, no significative displacement was registered when embedded inside the armour layer even in the amplification zone, unlike when placed on top of the filter layer where larger displacements were registered even under milder conditions. The

pipes also have shown some potential for sediment depositions and infills. Hence, these results point out the importance of accounting for the hydrodynamic shape, the submerged weight of the structures, the embedment into the protection layers, and the possible requirement of an anchoring system to keep stability while maintaining the ecological benefits. Nonetheless, the sediment infill can compromise the sheltering effect for biota and substrate species. Finally, regarding the stability of loose oysters and shells for cable protection, they have shown good behaviour in small hydrodynamic conditions. Significant displacements only started to appear for intermediate conditions. Nonetheless, no detrimental effects for the scour protection below were registered, highlighting the limited risk of this concept when compared to the installation of larger AR structures. Overall, as a scour protection ARs can have a positive effect on reducing turbulence on the foundations, depending on their placement.

Other alternative countermeasures, such as bionic grass (a low-maintenance fibre mat composed of several artificial grasses) and honeycomb protection (multi-compartment structure used in shoreline protection to improve growth of vegetation and restrict sediments motion), [Fig. 7](#), have also showed the capacity to decrease scour depths and enhance sediment depositions, [Schendel et al. \(2014\)](#).

Although alternative scour protection studies are gaining increasing momentum, they usually do not consider or quantify other important factors such as cost, adaptability, reliability, impact on biodiversity, marine environment pollution, and greenhouse gas emissions at the production level. However, a multi-criteria comparison was made by [Zhang et al. \(2023\)](#), taking into account factors such as adaptability, cost, environmental impact, concerns with the armour layer, soil improvement, pile attachment, seabed attachment, and biological protection for the most recent research findings in the literature. The conclusions extracted by [Zhang et al. \(2023\)](#) were that armouring layer protections (riprap and geotextiles), soil improvement techniques (MICP and ISS), and biological protections (bionic grass and ARs) had a higher overall score compared to active protection systems such as collars, vanes, and sacrificial piles active. Conversely, [Zhang et al. \(2023\)](#) points out the lack of practical application cases for soil improvement and biological protections. Moreover, [Zhang et al. \(2023\)](#) mentions that limited to no research has been performed on the impact of scour countermeasures on the marine environment, thus stressing that further

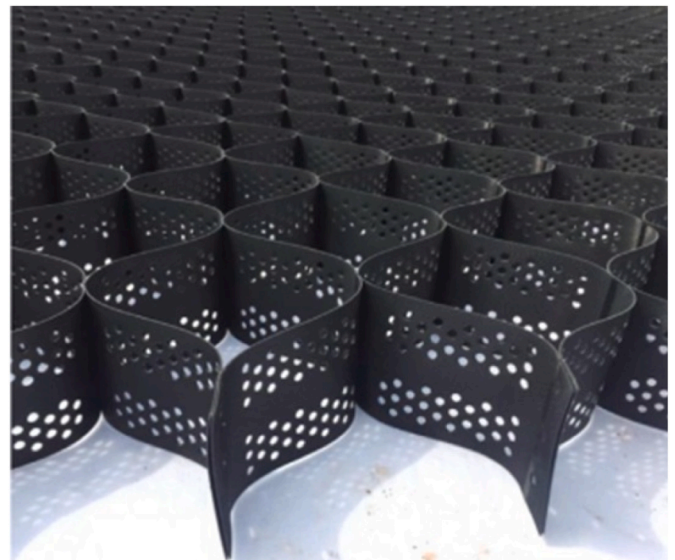


Fig. 7. - Honeycomb scour protection – Reprinted with permission from [Wang et al. \(2023a\)](#), Copyright 2023, Elsevier.

research should be made for a more comprehensive comparison.

In the end, both scour protection optimization and eco-friendly scour protection studies are crucial, as scour is a structural and financial risk and no design equations have been yet proposed or can be found in the literature, mainly for complex and hybrid bottom-fixed foundations. Typical solutions such as riprap protections have been proven to perform at a very high level in multiple engineering applications. It is now necessary to determine if the existing design formulas for monopiles are transferable and viable for other types of offshore foundations, or even if it is necessary, to improve them – to enhance cost reductions or improve savings of different in situ solutions when compared to the static protection concept. The following chapters will focus on scour and scour protection studies performed in complex and hybrid bottom-fixed foundations.

3. Scour and scour protections at complex foundations

In recent years, the focus of research related to marine renewables' energy has been looking to the possibility of co-located harvesting technologies, which require the development of hybrid foundations, i.e., a foundation where more than one technology can be installed. Given the possibility of risk and investment sharing among technologies that are simultaneously exploited, hybrid foundations represent a field of research with growing potential. The co-location of OWTs, WECs, TECs, and other technologies, often implies the use of marine foundations with complex geometries, that present scour behaviour that is rather different from the one presented by monopiles (Fazeres-Ferradosa et al., 2021).

Scour on complex bottom-fixed foundations, with complex geometries and features, has been increasingly discussed in recent years (Fazeres-Ferradosa et al., 2021). However, scour protections for these complex foundations are still a topic not fully addressed. With the application of energy converters, problems directly or indirectly connected to scour, such as instability, fatigue, or differential settlements, could be enhanced or diminished, thus directly affecting the protection behaviour.

The existing scour prediction and design formulas, and other scour countermeasures, were developed mainly for monopiles. Yet, for complex structures, those approaches are usually conservative and some methodologies do not translate directly, since they do not account for the foundations' different shapes or even for the increased importance of local scour (Fazeres-Ferradosa et al., 2021).

To better comprehend the basis of the scour on complex foundations and the structure features' influence on scour mechanisms, it is extremely important to understand scour around pile groups first. For wave-induced conditions, scour depths around pile groups not only increased with increasing Keulegan-Carpenter numbers (KC) and pile diameter (D_p), but was also highly reliant on pile spacing G/D_p – being G [m] the gap between piles (Sumer et al., 1992). For currents, scour on the pile group surrounding areas, is primarily caused by the increased flow velocity that bursts between the piles' gaps – aggravating the turbulence generated by each individual pile (Sumer et al., 2005).

The interference that an arrangement of two or more pile groups can have on each other could be detrimental, either by placing them “side by side” or “in tandem”. For piles “in tandem”, the possibility of local scour holes overlapping could lead to a larger scour pit between piles. However, a sheltering effect can also occur at the downstream pile, due to the flow obstruction combined with sediment depositions (Welzel, 2021). Qi et al. (2019) presented similar conclusions when using waves and currents on tandem piles, as the horseshoe vortex on both piles loses swirling strength, thus leading to a scour depth reduction.

For piles placed “side by side”, it was observed that when $G/D_p = 0$, scour depths were two times higher compared to a single pile (Beg, 2008). That difference only thinned for a $G/D_p > 6$, in line with the reports of Breusers (1972), stating that hydrodynamic interactions only start to become negligible for distances larger than $6D_p$.

These findings indicate that scour around complex foundations may

be heavily reliant on additional structural elements and features. A more comprehensive description of the concepts derived from scour at pile groups to complex foundations was taken by Welzel (2021). This review seeks to summarize the most recent research carried out on scour and scour protections for bottom-fixed complex foundations.

3.1. Jackets

Jackets are structures assembled with steel tubular elements, suited for intermediate waters – heavily used on offshore oil and gas platforms. It is the second most common type of foundation used for offshore wind turbines (Fig. 3), and the most popular among complex foundations (WindEurope, 2021b).

The different structural configurations of a jacket, according to the presence of other elements, such as the diagonal bracings, horizontal elements, and J-tubes, cause a blockage effect, altering hydrodynamic conditions. This results in flow contraction, increasing current velocities, lee side vortices, turbulence, and enhances sediment transport gradients, consequently increasing scour in the vicinity of the structure (Fazeres-Ferradosa et al., 2021). Some structural characteristics like diameter, angle, and distance between braces can magnify or diminish this blockage effect (Welzel et al., 2019a). A comparison of the scour depth between two jackets with different distances of the lowest node and diagonal braces to the seabed is validated by Welzel et al. (2020). This study also concluded that even a small change of the lowest node's distance can have a significant impact on scour, i.e., lower node and diagonal braces distances to the seabed lead to deeper local erosion in the piles' vicinities and increased erosion around the footprint area for a regime dominated by currents. However, there is less global scour in conditions where waves prevail.

When some in-situ scour depths were compared to predicted values of monopile's design formulas (Welzel et al., 2019a; Bolle et al., 2012), a discrepancy between values was detected. In fact, scour depths in the field can reach considerably higher values (Bolle et al., 2012). This reinforces the idea that more studies are still necessary to develop more accurate predictive formulas (Fazeres-Ferradosa et al., 2021).

Novel empirical expressions (Equation (7a)), based on the approach of Welzel et al. (2019a), account for the influence that the distance of both the node and the inferior diagonal brace nearest to the seabed can have on scour (Welzel et al., 2020) – where U_{cw} is the wave-current velocity ratio, and coefficient B is included to distinguish the impact of the distance to the seabed of the lowest node (Fig. 8). Parameter A differentiates the upstream (A_{front}) and the downstream (A_{rear}) sides of the structure. It is also a reference distance times the structure footprint length (Fig. 9), i.e., to estimate scour at the footprint $1.0A$ should be used, to estimate scour at an area of influence equal to two times the footprint $2.0A$ should be used, and so on.

As shown in Table 2, overall the S/D values tend to be higher for pile 1 (pile further ahead facing both waves and currents) than pile 3 (pile further back facing both waves and currents), indicating that the most exposed pile to hydrodynamic conditions has the most necessity to be protected. It also indicates that the relative scour depth tends to increase for higher values of U_{cw} for the same value of KC , showing that scour aggravates for increased hydrodynamic conditions mainly for current dominated conditions ($U_{cw} \geq 0.5$).

$$\frac{S}{D} = (0.7 + \exp(-6.5U_{cw}^{2.5} - A))^{1.5} + B \quad (7a)$$

with

$$A_{front} = 1.66KC^{0.34} - 4.5 \quad (7b)$$

$$A_{rear} = 1.30KC^{0.40} - 4.6 \quad (7c)$$

$$B = \begin{cases} 0.17, \text{node distance} = 0D \\ 0.22, \text{node distance} = 1D \end{cases} \quad (7d)$$

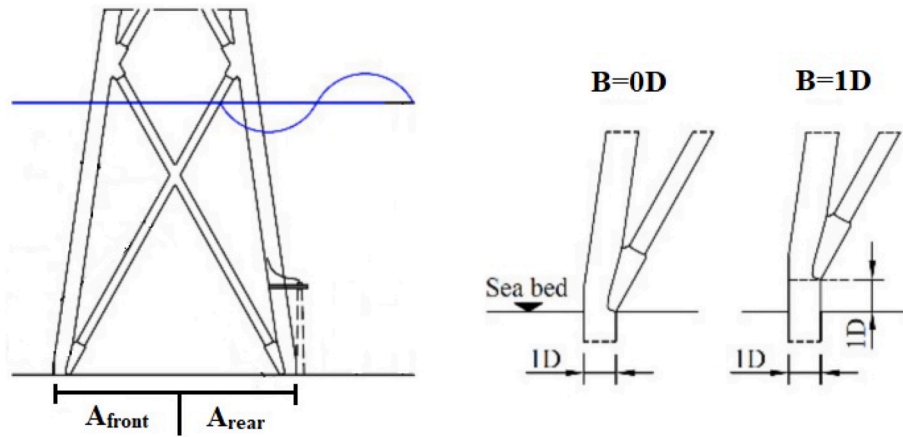


Fig. 8. - Visual representation of the parameters A and B – adapted from Welzel et al. (2020).

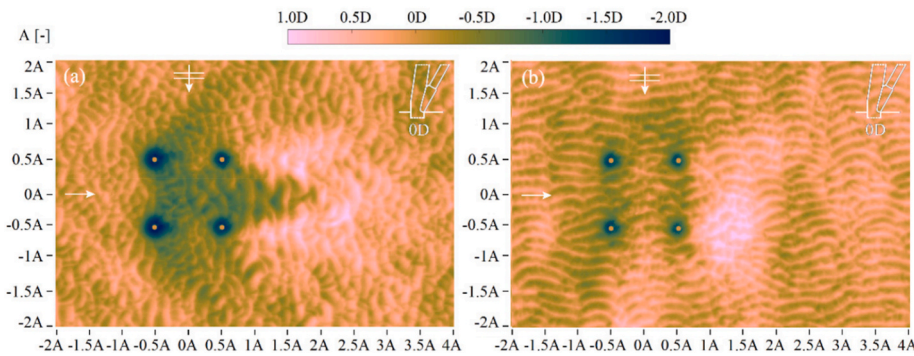


Fig. 9. Surface elevation for scour tests (node distance: 0D), over a distance A to the centre of the foundation (blue and green: scour, brown and pink: sediment deposition), for: a) $KC = 6.7$ $U_{cw} = 0.75$; b) $KC = 14.9$ $U_{cw} = 0.56$ – adapted from Welzel et al. (2020).

Table 2

- Test results and conditions for jacket scour tests (Welzel et al., 2020) – prototype values.

Test	Node Distance (m)	Hs (m)	Tp (s)	Um (m/s)	Uc (m/s)	Ucw (–)	Wave-Current Direction	KC (–)	S/Dpile1 (Front)	S/Dpile3 (Rear)
1	0D	4.41	10.95	0.73	0.55	0.43	90°	6.7	0.403	0.238
2					1.23	0.63			0.801	0.786
3					2.13	0.75			1.571	1.268
4		4.74	18.62	0.96	0.55	0.37		14.9	0.884	0.580
5					1.23	0.56			1.317	1.075
1	1D	4.41	10.95	0.73	0.55	0.43	90°	6.7	0.464	0.271
2					1.23	0.63			0.863	0.708
3					2.13	0.75			1.502	1.133
4		4.74	18.62	0.96	0.55	0.37		14.9	0.735	0.622
5					1.23	0.56			1.205	1.038

Also, new volume analysing methods, as well as dimensionless parameters were provided, capable of being adapted for offshore complex foundations (Welzel et al., 2019b). It also includes the derivation of equations to predict maximum erosion volumes (Equation (8)) and cumulative erosion volumes (Equation (9a)), over a certain distance A to the centre of the structure. The tests revealed that the area of the seabed affected by the structure is considerably larger (between 2.1 and 2.7 times the structure's footprint), where the maximum erosion intensity appears to be found in the vicinity of an area equal to 1.25 times the structure's footprint area.

Global and local scour give different indications of scour patterns around the structure. Local scour indicates that the scour holes develop mainly around the foundation piles, whereas global scour indicates that the scour rate and depth are extended around the entire jacket foundation (Welzel et al., 2019b). A comparison between local and global erosion volumes revealed that, for wave-dominated conditions, scour

depth and patterns are dominated by local scour (68%), opposite to current-dominated conditions, mainly for $U_{cw} \geq 0.75$, where scour depth and patterns are governed by global scour (67%), (Welzel et al., 2019b). These values indicate that for zones where hydrodynamic conditions are dominated by waves, scour protections should be designed only for each pile or reinforced with a higher thickness near the piles, whereas for current-dominated zones, scour protections should be reinforced near the piles but also designed for a much higher extent, to cover the structure's footprint area and the surroundings.

Although both studies do not consider scour protections, they could be helpful to develop them. They provide valuable information about scour patterns (Fig. 9), scour depth (Table 2), and erosion volumes, indicating the extent, thickness, and where the scour protection should be reinforced. Moreover, the results when compared to in situ data (Bolle et al., 2012; Baelus et al., 2018; Rudolph et al., 2004) showed good correspondence (Welzel et al., 2019b).

$$V_{A,max} = -1.3(0.1 + \exp(-4.6U_{cw}))^{1.5} \quad (8)$$

$$V_{A,i} = V_{Area} - 1.3(0.1 + \exp(-4.6U_{cw}))^{1.5} \quad (9a)$$

with

$$V_{Area} = \begin{cases} ((0.1 + \exp(-10A + 8))^{-0.9} B' - C', A < 1.25A \\ -2.2 \exp(-0.7A) - 0.11, A > 1.25A \end{cases} \quad (9b)$$

$$B' = (-5.2U_{cw} + 6.9)10^{-2} \quad (9c)$$

$$C' = (3.8U_{cw} + 4.9)10^{-1} \quad (9d)$$

Recently, [Welzel et al. \(2024\)](#) performed a comparative study of a novel complex foundation to a standard 4-legged jacket, under unidirectional currents in clear-water and live-bed conditions. The description and results of the novel foundation are reported on Chapter 3.5. Regarding the jacket foundation, [Welzel et al. \(2024\)](#) reported that for clear-water regime no global scour was observed, being apparent that the foundation's structural elements and features have a small influence on the scour process. It was observed that local scour holes increase faster at the upstream piles that shelter the downstream piles. During live-bed conditions, the foundation showed the presence of global scour since erosion was detected around the piles and in centre of the foundation. Nonetheless, global scour progressed slower than local scour. Moreover, sediments began to accumulate downstream of the structure. When compared to the results of combined wave-current conditions of [Welzel et al. \(2019a\)](#), the scour development observed by [Welzel et al. \(2024\)](#) shows higher disparities in the local scour development between the upstream and downstream piles. [Welzel et al. \(2024\)](#) also compared its results to in-situ field data, verifying a good agreement of the erosion spatial distribution and mean dimensionless scour depths.

Some of the observations under clear-water regime reported by [Welzel et al. \(2024\)](#) are corroborated by the experimental campaign performed by [Chen et al. \(2023\)](#) on 4-legged jacket under unidirectional currents. [Chen et al. \(2023\)](#) tested different flow directions (by rotating the foundation), different water depths, different flow strengths (ratio between the current-averaged velocity and the critical velocity of sediments), and in the end performed a result comparison to a monopile. The major conclusions are outlined below.

- For a 0° foundation angle (two piles facing currents), maximum scour depths occur at the front piles. The back piles due to a sheltering effect and due to the eroded sediments from the front piles, registered lower scour depths;
- For a 45° foundation angle (one pile facing currents), the maximum scour depths occur at the middle row of piles, as the flow behind the front pile increases and the change on the position of the upper truss enhances turbulence;
- Variations on the foundation angle reduce the sheltering effect of the front pile(s), as the remain piles begin to be directly affected by the incoming hydrodynamic conditions and the reduction of the distance between the front piles increase the jet flow effect;
- Maximum scour depth is directly related to the flow strength and water depth if the remaining conditions are kept constant. Moreover, the time for scour to reach a quasi-equilibrium stage increases with increasing flow strength;
- The scour process on a monopile tends to be slower and the maximum scour depth and extent are lower when compared to a jacket foundation, indicating that the structural elements and features have a strong influence;

Numerical models were also performed to compare predictive values with in-situ measurements. Numerical simulations of the C-power wind farm Thornton Bank, under currents and waves, were carried out to predict local scour ([Ahmad et al., 2020](#)). The results of maximum scour agreed well with the reports for a 4-pile jacket foundation ([Bolle et al.,](#)

[2012](#)). A numerical model of a multi-bucket jacket foundation that resulted in the suggestion of a scour prediction formula for currents based on dimensionless parameters for a certain range of values ([Table 3](#)) was also developed ([Lian et al., 2022](#)).

Few recent works tested scour protections for jacket foundations. An extensive review of those works can be found in [Fazeres-Ferradosa et al. \(2021\)](#).

[Table A.1](#) gives a brief overview of some physical model tests. The main conclusions of those studies are as follows.

- An East Anglia One offshore wind farm 3-legged jacket foundation model ([Fig. 10](#)), with front mats and high-density rip rap scour protections, has been tested for three cumulative sequential tests of waves and currents (ascending, descending, and random), [Sarmiento et al. \(2021\)](#). The erosion patterns were similar for all sets of tests. It was concluded that a decreasing sea state sequence leads to larger erosion and cumulative damage when compared to an increasing or random sequence. For the most exposed jacket leg, a maximum scour depth equal to $5D_{50}$ was registered for the descending sequence. As for the ascending and random sequence, the maximum scour depth value obtained was equal to $3D_{50}$. The least exposed jacket leg registered a maximum scour depth of $2D_{50}$ for the least favourable sequence of tests. Regarding the scour extent, the worst case was also recorded for the descending sequence, over the ascending or random sequence (approximately $0.5D$ from the edge of the jacket leg);
- Jacket foundation models of the HZK Offshore Wind Farm and the Borssele Wind Farm and OHVS ([Fig. 11](#)), respectively, with different displacements of the material of the scour protection have been tested ([Van Velzen et al., 2016](#); [Van Velzen and Bruinsma, 2017](#); [Bruinsma et al., 2018](#)). Three different configurations of the scour protections were studied: a single layer with a post-installed jacket and a two-layer system with a post- and pre-installed jacket. Results showed some similarities between both studies and concluded that the scour protection was quite stable, either applied pre- or post-installed jacket. The two-layer system, with the armour layer placed after the jacket's installation, was deemed the worst option regarding the armour layer stability. The study also highlights the importance of the filter layer in a two-layer protection system;
- A 4-layer scour protection around a jacket foundation model for waves and currents ([Fig. 12](#)), as well as an alternative, soft scour countermeasure, i.e., coastal cage net for aquaculture was tested ([Hsin-Hung et al., 2014](#)). Both solutions proved to be effective and resulted in a reduction of the scour depth. Moreover, the integration of a coastal cage net shows that it can be meaningful and helpful to prevent scour around offshore foundations;

While there is a clear lack of studies on scour protections applied to jackets, in recent years, the number of scour model tests performed on jackets has been increasing for both physical models ([Welzel et al., 2019a, 2019b, 2020](#); [Hsin-Hung et al., 2014](#)) and numerical models ([Ahmad et al., 2020](#); [Lian et al., 2022](#)). They aim to cover important parameters such as the relative scour depth (S/D), the scour width, the dimensionless time scale (T^*), the equilibrium scour depth (S_{eq}), eroded

Table 3

– Numerical model conditions by [Lian et al. \(2022\)](#).

Reference	Lian et al. (2022)
d (m)	40
U_c (m/s)	1
U_{max} vortices (m/s)	[1.35–2.76]
Calculation time (s)	3600
Output time (s)	300
Bucket Diameter (m)	[10–30]
Bucket Spacing (m)	[30–50]
Bucket Exposed Height (m)	[0–3]
Hydrodynamic Load	Currents only



Fig. 10. - Scour protection for a model of the East Anglia One 3-leg jacket (Sarmiento et al., 2021).



Fig. 12. - Scour protection model for a 4-leg jacket (Hsin-Hung et al., 2014).

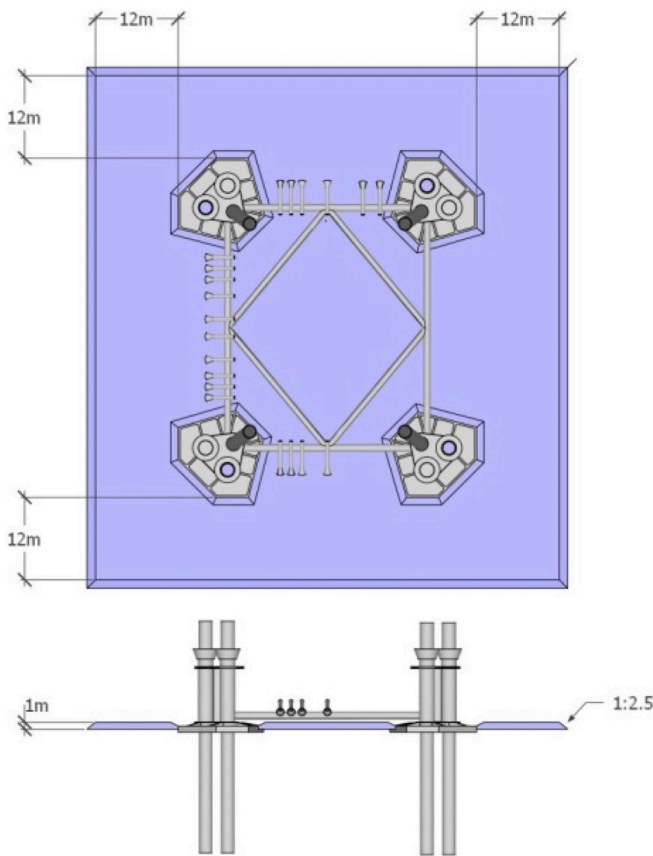


Fig. 11. - Scour protection layout for a 4-leg jacket model of the Borssele Offshore High Voltage Station (Bruinsma et al., 2018).

volumes and areas, and scour estimations when a regime is dominated by currents, by waves or equally dominated. One of the reasons is that there has been a growing interest in reusing old platforms to install OWTs, but also in using jackets for offshore high-voltage stations. In addition, there has been an increased effort to develop scour design equations since monopile's formulas predict inaccurately the phenomena for complex structures. New findings can serve as a base and lead to further studies to develop novel dynamic design formulas for scour protections.

3.2. Tripod foundations

Tripods are complex structures composed of three piles connected to the main column by diagonal braces, best suited for intermediate waters. Studies involving scour protections for this type of complex structure are not common. The scour process and its development for tripods are quite different from monopiles or even from sets of piles.

Tests with tripods, hexapods, a triangular array of circular cylinders (TACC), and a hexagonal array of circular cylinders (HACC), have been performed under currents, and compared to each other and monopiles (Ni and Xue, 2020). The work shows that the relative maximum scour depth (S_{end}/D) is approximately 30% higher for tripods and hexapods than for TACCs and HACCs, respectively, proving that the lower diagonal braces of the complex structure cause blockage effects, enhancing scour phenomena.

A setup of physical and numerical model tests to assess scour on tripods under regular waves (scale: 1:40, $H = 8.25$ m, $T_m = 19$ s, and $d = 30$ m – prototype values) was performed for a 4000-wave cycle. Scour was observed under the main column, around the lower braces connecting the piles to the columns, and at the front/rear piles. For the physical model, the rear piles registered the highest relative scour depth ($S/D_{pile} = 0.85$). As for the front pile, S/D_{pile} decreased to 0.59, and under the main column, S/D_{column} was equal to 0.44. Scour under the main column and the lower braces can be explained due to the blockage effects mentioned in Ni and Xue (2020). Scour depths were in an almost equilibrium stage after 3000 waves, with 90% of the corresponding values reached after 1500 waves. The scour patterns identified were similar to other researchers' findings (Stahlmann and Schlurmann, 2010; Harris and Whitehouse, 2014). Regarding the numerical model, for the front pile, scour depths were in good agreement with the experimental results. However, scour depths at the rear pile and under the main column were about 20% lower and 32% higher, respectively. This difference had not a clear explanation, and it was assumed to be related to hydrodynamic processes and wave absorption procedures.

The research comparison between in-situ data (Alpha Ventus Offshore wind farm), large-scale (1:12), and small-scale (1:40) tests performed by Stahlmann and Schlurmann (2010) allows to extract similar but further conclusions from those in Stahlmann (2014). The tests were performed for regular and irregular wave cycles, for different incoming wave angles (Fig. 13): 0° - one pile facing waves, 30° - asymmetric constellation, and 60° two piles facing waves. Table A2 gives a brief overview of the setup conditions, some of the S/D values obtained for the 0° configuration under regular waves with maximum wave height and period, and the in-situ measurements.

Overall, both the large- and small-scale tests allowed to state that global scour (highly related to scour extent) and local scour (highly

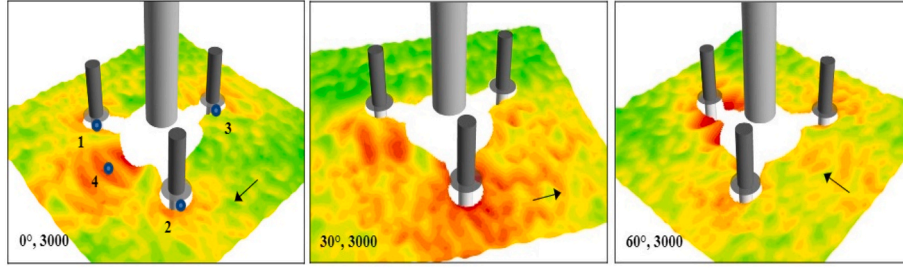


Fig. 13. – Scour development for different incoming wave angles – adapted from Stahlmann and Schlurmann (2010).

related to scour depth) were very dependent on the wave direction. Comparing the results between both scale tests, it was worth noticing that the 1:12 tests obtained S/D values for the structural elements almost 50% higher than the small-scale tests. As for the near field of the structure, the difference was explained by the influence of the ripple formation. The large-scale tests also showed that regular wave conditions, with wave heights and periods similar to irregular wave conditions, led to higher sediment mobility around the structure, increasing global scour – despite local scour at the piles and under the main column reaching similar values (Stahlmann and Schlurmann, 2010). Regarding the in-situ measurements, when compared directly to the large-scale tests, the registered S/D values were larger, mainly under the main column. These differences were attributed to the tested model wave conditions (real sea state conditions and wave directions were simplified), scale effects of the sediments (not properly scaled to maintain non-cohesive properties), and mainly the fact that only waves were used, instead of real wave-currents offshore conditions (Stahlmann and Schlurmann, 2010). However, both models had a good agreement with the in-situ measurements regarding the development and extent of local and global scour – maximum scour depths and shapes occur at similar spots.

For tests under currents and waves, a tripod with 3 different orientations was studied (Hu et al., 2021), according to the position of the wave-current direction: (i) 0° - a pile facing the wave-current direction; (ii) 90° - asymmetric, with the wave-current direction being perpendicular to a brace; and (iii) 180° - two piles facing the wave-current direction. The maximum scour occurs beneath the main column, while the scour patterns extend into the area of the inferior diagonal braces as in Heibaum et al. (2010). The aforementioned blockage effect explains these characteristics, which increase the shear stress on the seabed by causing streamlined contraction (Hu et al., 2021). However, results also showed that for the 90° orientation, a higher S/D value was reached. The following main conclusions can also be stressed (Hu et al., 2021).

- diagonal braces facing waves and currents increase the blockage effect;
- when currents are superimposed, the dimensionless time scale for a 90° orientation increases, thus the equilibrium states are achieved for a longer time-scale;
- the comparison of experimental data with predicted values of the equilibrium scour depth formula (Sumer and Fredsøe, 2002), Equation (10a), revealed that the experimental results were on average 25% higher, for the 90° orientation. Therefore, it recommends the use of a safety coefficient of around 1.3 when using the following equation.

$$\frac{S_{eq}}{D} = (S_{currents} / D) \cdot \{1 - \exp[-A' \cdot (KC - B')]\}; KC \geq 4 \quad (10a)$$

$$A' = 0.03 + 0.75 U_{cw}^{2.6} \quad (10b)$$

$$B' = 6 \exp(-4.7 U_{cw}) \quad (10c)$$

The results obtained, indicate that probably some of the current

methodologies could be adapted to predict scour and possibly to design scour protections for tripods (Hu et al., 2021). Therefore, it proposes two new equations that relate the S_{eq} with the Froude (Fr), Equation (11), and Euler number (Eu), Equation (12), for waves and currents. The results reveal that S_{eq} increases gradually and approaches an asymptotic value when Fr and Eu increase. Hu et al. (2021) considers that both formulas give a general representation of the scour depth varying trend, despite some discrepancy between the experimental data and fitting results – experimental data generally distributed within a margin of error of $\pm 30\%$. In the end, it recommends that scour protections around tripods should have larger thicknesses when compared to monopiles and be reinforced in critical areas such as under the main column and diagonal braces.

$$\log(S_{eq} / D) = -0.23 \exp(0.33 / Fr) + 0.49 \quad (11)$$

$$\log(S_{eq} / D) = 0.34 \exp(-0.05 / Eu) - 0.16 \quad (12)$$

A numerical model for random waves was performed, Hu et al. (2022c), and compared with other experimental investigations (Sumer and Fredsøe, 2001; Schendel et al., 2020). The model proved to be capable of predicting both equilibrium and maximum scour depth with relatively satisfactory accuracy. The maximum error between the numerical results and experimental values, (Sumer and Fredsøe, 2001; Schendel et al., 2020), was less than 30% in most of the cases. Moreover, all scour patterns (Hu et al., 2022c) were similar and followed the results achieved by several studies (Stahlmann and Schlurmann, 2010; Stahlmann, 2013, 2014).

It is evident that the works found in the literature are still insufficient and solely address scour depths and inherent patterns. Studies regarding scour protections for offshore wind tripod foundations were not found by the authors. Nevertheless, the information provided about local and global scour development lays a foundation for future studies of scour protection's damage and protection design since, like other complex foundations, tripods differ considerably from monopiles in terms of scour behaviour.

3.3. Gravity-based foundations (GBFs)

Gravity-based foundations (GBF) are heavy concrete structures, suited for shallow waters, and are designed so that their self-weight withstands high overturning moments. Scour and scour protections on GBFs are less studied than in jackets or monopile foundations. The majority of studies are performed by private companies, which generally do not provide sufficient data for the public due to restricted confidential policies of the sector (Fazeres-Ferradosa et al., 2019a).

Guidelines for scour management plans, and a review of scour and protections emphasize that, in non-cylindrical GBFs, some areas are more susceptible to scour due to blockage effects around their edges (Whitehouse et al., 2011b). These observations were also noticed in a model of a STRABAG foundation – a reinforced and sand-filled concrete foundation with a cross-shaped base – subjected to physical and numerical studies (Wilms et al., 2012). As a scour protection, instead of a rubble-mound armour layer, container protection with two-layered

sand-filled geotextile was used (Fig. 14).

Scour tests performed in a large physical model, with a scale of 1:17, Wilms et al. (2012) showed that the zones more prone to scour occur at the front and back shaft, bracings, and lee corners of the hollow boxes. It was concluded that sand containers were hydraulically stable as a scour protection. The numerical model showed that the foundation's cross-shaped format caused an increment in the flow field and velocities, due to the blockage effect, enhancing the scour process (Wilms et al., 2012). The manuscript also includes a small analysis and comparison of the S/D , for a non-protection and protection scenario, revealing that overall scour development had a high rate between 500 and 1000 waves, which then gets reduced slightly for 2000 waves. In the cases where the protection was used, it was observed that scour depths and widths were smaller, and the major difference in the results was obtained for 5000 waves, where the S/D value represents almost half of the value obtained on the model without protection. Given the usage of geotextile containers as scour protection, dynamic behaviour was not examined.

An application of a dynamic scour protection to a gravity foundation to investigate scour around a model of the offshore converter DolWin Beta was studied in De Sonneville et al. (2014). The scour protection applied around the rectangular foundation did not present a uniform thickness, since a different methodology was used, i.e., the reinforcement of critical areas and the usage of a smaller thickness on sheltered zones. Dynamic stability was observed for the conditions used, even if only for 2000 waves. It was concluded that the use of stones with larger density can be used for optimization purposes since enhanced stability was achieved for reductions in volume and rock size. It also determined that currents have major importance in scour even for a wave-dominant regime.

A physical model study of dynamic scour protection for the Adriatic Liquefied Natural Gas (LNG) terminal (Fig. 15) was performed by Chen et al. (2011). The structure was composed of a gravity-based structure (GBS) and two mooring dolphins. The objective was to determine the maximum scour depth, assess if a filter layer was necessary, and evaluate the edge scour of the protection. For a 1:50 scale, four scour protection layouts were submitted to wave and current conditions (Table A3) for a 100-year return period from the project site Bora winds – result in waves from North-East to East directions – and Scirocco winds – result in waves from the South-East direction. The final design consisted of an armour layer with varying thickness, varying width, and without a filter layer. The study concluded that the scour protection sustained limited damage and that the optimized layout version had an increment of the protection thickness at the mooring dolphins, and a decreased width around the main structure. The results have shown that the sharp corners of the mooring dolphins cause significant erosion. At the main structure, scour

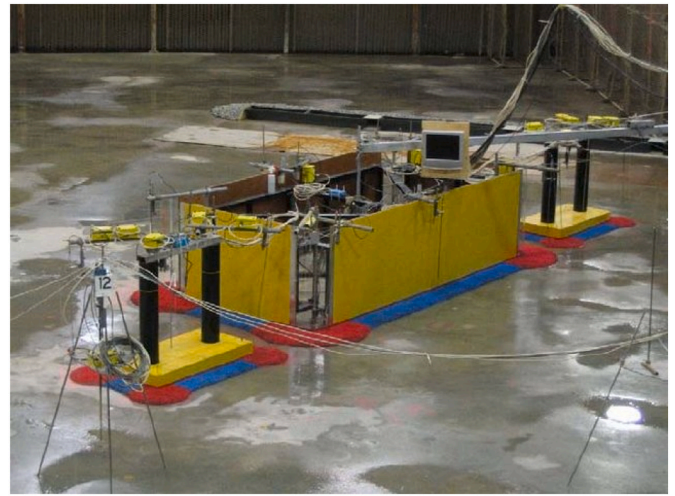


Fig. 15. - Scour protection of the Adriatica LNG terminal and mooring dolphins (Chen et al., 2011).

was also more severe in corners than around the structure's edges.

Another work regarding GBFs and scour protections provides some evidence that in a wave-dominated regime, the amplification factor of the bed shear stress is smaller than 2, Tavouktsoglou (2018). It also proposed an equilibrium scour depth formula (Equation (13a)) for complex and uniform structures, reliable for currents only but conservative for offshore conditions – where D_{base} (m) is the diameter of a non-uniform cylindrical structure, ζ is a parameter that relates the Reynolds number of the structure (Re_D), the flow depth (h [m]), the Froude number (Fr), the Euler number (Eu), the depth-averaged flow velocity (U_c [m/s]), and the mean threshold velocity of sediments (U_{cr} [m/s]), and $c1$, $c2$, $c3$ are fit coefficients. Therefore, an alternative design option based on the threshold of motion could be a future approach as stated by Fazerres-Ferradosa et al. (2021). Table A3 reports a summary of the physical models performed on scour protections for GBFs presented in the literature.

$$\frac{S}{D_{base}} = \frac{c1\zeta + c2}{\zeta + c3} \quad (13a)$$

with

$$\zeta = \left(\frac{1}{\log(Re_D)} \right) \left(\frac{h}{D_{base}} \right) (Fr)(Eu)^{0.5} \left(\frac{U_c}{U_{cr}} \right)^{0.5} \quad (13b)$$



Fig. 14. – Scour protection model of a STRABAG foundation using geotextile containers (Wilms et al., 2012).

$$c1 = [2.1, 2.3] \quad c2 = [-0.009, 0.005] \quad c3 = [0.01, 0.05] \quad (13c)$$

Gao et al. (2023) took a different approach by performing an experimental research comparison of 7 different scenarios for a 1:100 geometrically scaled GBS. The model composed of two pontoons, six supporting columns, and cross braces was tested for currents-only and waves-only conditions, for two different angles (Fig. 16): 0° and 90° . The scenarios tested compared an unprotected GBS with 6 different scour protection solutions (Fig. 18): geotextile, riprap, geotextile-riprap, bionic grass, bionic grass-geotextile, and bionic grass-geotextile-riprap. To measure scour the author used a laser scanner to extract the three-dimensional bed topographies. It was concluded that currents were the most severe hydrodynamic condition, as the relative maximum scour depth at the pontoons ($S_{\max}/D$) of 1.12 was obtained for currents-only (90° direction) when compared to 0.193 for waves-only (90° direction), for the control scenario (no protection). When the highest U_c value was applied in the 90° direction, the platform tilted and collapsed.

By determining which was the most severe condition, Gao et al. (2023) continued the test program by implementing 6 different scour protection systems. The tests have shown that “usual” scour protections, such as riprap protections had an efficiency of reducing the scour depth of 7.0% and 55.6% when compared to the control scenario, for currents at a 0° and 90° directions respectively (Fig. 17). The geotextile-riprap, another common type of scour protection system applied in physical model tests, had an efficiency of 44.4% and 49.8%, for currents at a 0° and 90° direction respectively (Fig. 17).

The values demonstrate that the geotextile-riprap system has a more consistent performance for multiple hydrodynamic condition directions when compared to the riprap protection, with a surplus of 37.4% for the 0° direction (despite having a slightly worse performance for the 90° direction). In part, this answers some questions in the literature as to what the best filter layer material is and what are the differences in performance of the geotextile filter.

Regarding the performance of all 6 scour protections, by observing Fig. 17 it can be concluded that the bionic grass, the bionic grass-geotextile, and the bionic grass-geotextile-riprap systems were the best protection systems efficiency-wise by reducing scour in orders of 68.7% (0° direction) and of 80.1% (90° direction). The worst solution was by far the application of an only-geotextile system, with a residual efficiency for the 0° direction and a negative efficiency for the 90° direction.

Results show that perhaps the application of new and alternative materials such as bionic grass, when combined with common materials such as riprap, could be the true and ultimate optimization of scour protections. Nonetheless, to confirm the results of Gao et al. (2023), new tests with a more realistic offshore condition such as the combination of waves and currents should be applied to assess the true efficiency of the different scour protection systems used.

However, although few research studies have been made on scour protections for GBFs, the number of works is not sufficient to cover a

substantial range of offshore conditions, to address or evaluate the dynamic behaviour of such protections, nor to present or optimize novel design formulas for this type of foundation. Hence, the present review highlights the importance of extending such testing conditions as a contribution to the development of scour protection design methodologies for GBFs.

3.4. High-rise structure foundations (HRSFs)

High-Rise Structure Foundation (HRSF) is a bottom-fixed structure widely used in the Asian OWS, due to the shallow depths of some Asian seas, as they represent a safe, reliable, and economical alternative (Li et al., 2017; Xiao et al., 2021; Sánchez et al., 2019). However, according to the data collected by Sánchez et al. (2019) HRSFs have a limited optimal range of use as they only have been used until a maximum depth of 15 m and 15 km distance to the coast. It consists of a permeable foundation composed of multiple inclined piles in circular arrays that support a platform (cap), bearing high stability to axial loads, horizontal loads, and bending moments (Xiao et al., 2020, 2021; Li et al., 2017). Due to its complex layout, the flow passing through the foundation reduces the downflow and the strength of the horseshoe vortex, due to the so-called bleed flow – leading to considerable differences in the scour depth and patterns observed on monopiles (Xiao et al., 2020, 2021). Hence, equilibrium equations from monopiles tend to be conservative and overpredict scour depths at HRSFs (Xiao et al., 2021). As far as scour protections, to the authors’ knowledge, there are no studies in the literature, since there have been only even a few studies covering scour for this type of foundation.

To cover some of the gaps, a comparative study between a high-rise pile foundation and a monopile was performed by Xiao et al. (2020) and by Xiao et al. (2021), using both an 8-pile and a 10-pile HRSF. The tests were performed for a scale factor of 1:50, for multiple alignment angles, and as far as the hydrodynamic conditions tested, both studies used currents-only (Table A4).

Both authors reached similar conclusions: the maximum scour depth (Fig. 19) generally occurred around the middle row of piles, $S/D_e = [0.5 \text{ to } 1.1]$, and was lower than the registered on the monopile, $S/D = [1.5 \text{ to } 1.7]$ – being D_e [m] the equivalent diameter of the foundation, i.e., the diameter of a monopile which has an equal cross-sectional area to the HRSF and d_p [m] the diameter of each HRSF individual pile (Equation (14)). For monopiles, $D_e = D_p$. This was credited in part to the structural permeability, the sheltering effect of the upstream and middle piles, and the bleed-effect of the foundation. Xiao et al. (2020) observed that a higher single dune of sediment depositions occurred closer to the high-rise pile foundation when compared to two smaller dunes appearing further away from the monopile (Fig. 19). This feature was attributed to the fact that the HRSF piles decrease the sediment transport capacity of the penetrating flow. As far as the scour shape of the global scour hole, it has a serrated shape, opposite to a smooth circular profile of the monopile. The radial distance of the scour hole increases in the

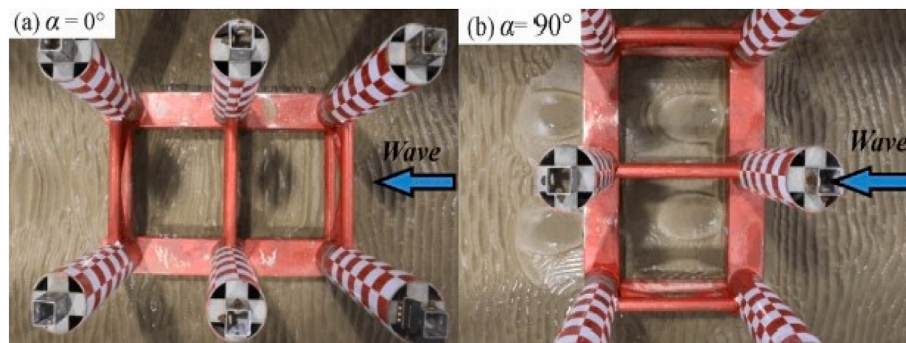


Fig. 16. - GBS submitted to waves-only for: (a) 0° direction and (b) 90° direction – Reprinted with permission from Gao et al. (2023), Copyright 2023, Elsevier.

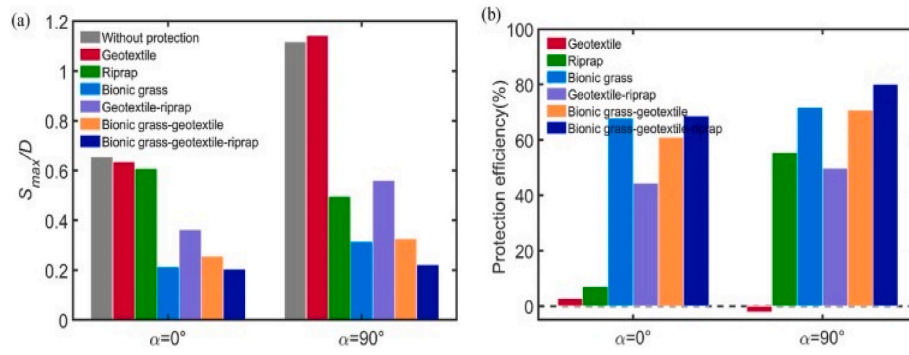


Fig. 17. - S_{max}/D and Protection Efficiency (%) for different scour protection systems for the maximum flow velocity ($U_c = 0.25$ m/s), Reprinted with permission from Gao et al. (2023), Copyright 2023, Elsevier.

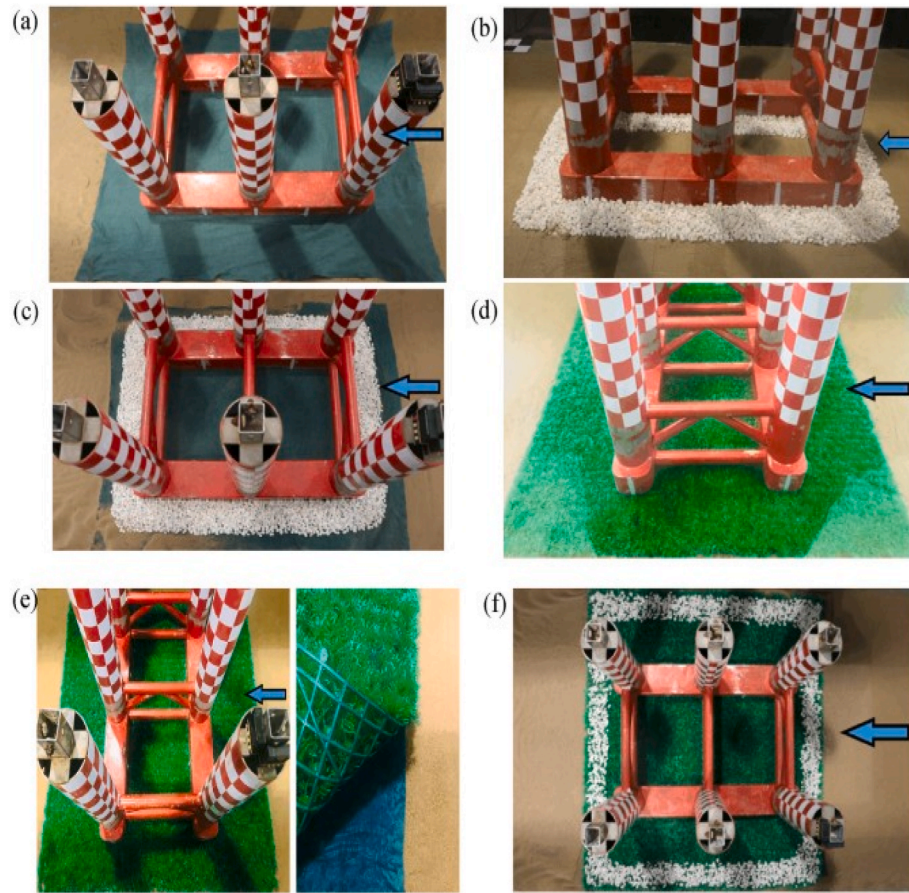


Fig. 18. – GBS scour protection systems: (a) geotextile; (b) riprap; (c) geotextile-riprap; (d) bionic grass; (e) bionic-grass-geotextile; (f) bionic grass-geotextile-riprap – Reprinted with the permission from Gao et al. (2023), Copyright 2023, Elsevier.

flow direction, changing from $1.36D_e$ (upstream) to $2.35D_e$ (downstream). Compared to the radial distance of the monopile ($2D_p$ to $4D_p$), it is possible to conclude that scour occurs much closer to the vicinity of HRSF.

$$D_e = \sqrt{nd_p} \quad (14)$$

With the results obtained, Xiao et al. (2020) proposed a formula to predict scour radial distance (Equation (15)) and the equilibrium scour volume (Equation (16)) that can be useful for designing the minimum area of a scour protection armour layer.

$$\frac{R'}{D_e} = k' \frac{d_s}{D_e} \quad (15)$$

$$\frac{V_s}{V_{se}} = 1 - \exp \left[-1.29 \left(\frac{t}{T_e} \right)^{0.46} \right] \quad (16)$$

being R' [m] the radial distance of scour (horizontal distance from the outer edge of the exposed piles, d_s [m] the local scour depth at an individual HRSF pile, k' [-] the constant to define the upstream (1.57), the side (1.87), and the downstream location (2.99) of the foundation, V_s [m³] the scour volume, V_{se} [m³] the equilibrium scour volume, t [s] the scour time step, and T_e [s] the scour time scale.

Table 4

Field measurements for the Dogger Bank and Horns Rev II suction bucket foundations - adapted from Stroescu (2018).

Reference	Dogger Bank East	Dogger Bank West	Horns Rev II
d (m)	25	23	20
D_{caisson} (m)	15	15	12
10-year Return Period: Wave height (m)	9.1	9.8	8.1
10-year Return Period: Wave period (s)	16	15	12
Flow velocity (m/s)	1.0	1.0	[1.5–2]
θ_{cr} [°]	0.074	0.074	0.030
τ_{cr} [MPa]	0.161	0.161	0.224
Installation time (h)	6	7.5	8
Equilibrium scour depth (m)	[0.5–0.8]	[0.5–1.4]	[0.4–0.9]
Max scour depth (m)	1.5	1.9	2.0
$S_{\text{max}}/D_{\text{caisson}}$	0.1	0.126	0.166

Xiao et al. (2021) concluded that the alignment angle of the foundation facing the hydrodynamic conditions, had a negligible effect on the scour rate and the equilibrium scour depth. It proposed an empirical formula for estimating the equilibrium scour depth (Equation (17)).

$$\frac{d_{se}}{D_e} = 3.08 \left(\frac{d}{D_e} \right)^{0.40} \left(\frac{U_c}{V_c} \right)^{5.18} \left(\frac{D_e}{D_{50}} \right)^{-0.14} \quad (17)$$

being d_{se} [m] the equilibrium scour depth for HRSF individual piles and V_c [m/s] the threshold sediment motion velocity.

According to the author, this equation cannot be applied when U_c/V_c

< 0.75 . However, it showed a good agreement with the available data, having the smallest root mean squared and mean absolute error when compared to existing empirical equations for monopiles. Almost all the prediction values were within the $\pm 20\%$ error lines, way lower than the $\pm 50\%$ error lines of the comparable equations.

Liang et al. (2021) also performed a series of small-scale tests to assess the characteristics of the turbulent flow fields around a 10-pile HRSF, (Table A4). It concluded that the first and second rows of piles cause an increase in the flow velocity, reaching its maximum value at the third (middle) row of piles. For small Reynolds numbers, the wake vortices could not fully be developed on the leeward side of the last row of piles – contrasting to what occurs in monopiles. The strong flow velocities and turbulence around the middle row, lead to severe scour depths around this area, to the occurrence of a long-tail pattern downstream of the foundation shoulders, and a trapezoidal deposition of seabed sediments behind the HRSF. These findings are supported by the observations of Xiao et al. (2020, 2021).

A similar study was conducted by Yagci et al. (2017), where clear-water scour was analysed for an array of circular piles, one central cylinder surrounded by other six cylinders at the vertices of a regular hexagon. Different configurations regarding the flow direction alignment and solid volume fractions (i.e., placement density of the piles) were used to determine the effects of permeability, blockage effects, and angle of attack of the flow. When comparing the results to a singular pile with an equal cross-sectional area, overall, the arrays could generate 22% less scour depth and 27% less scour volume. As stated by Yagci et al. (2017), the cross-sectional area of the array may impact the temporal development of scour. However, scour depth increment is influenced mainly by the orientation and placement density of the piles, as a

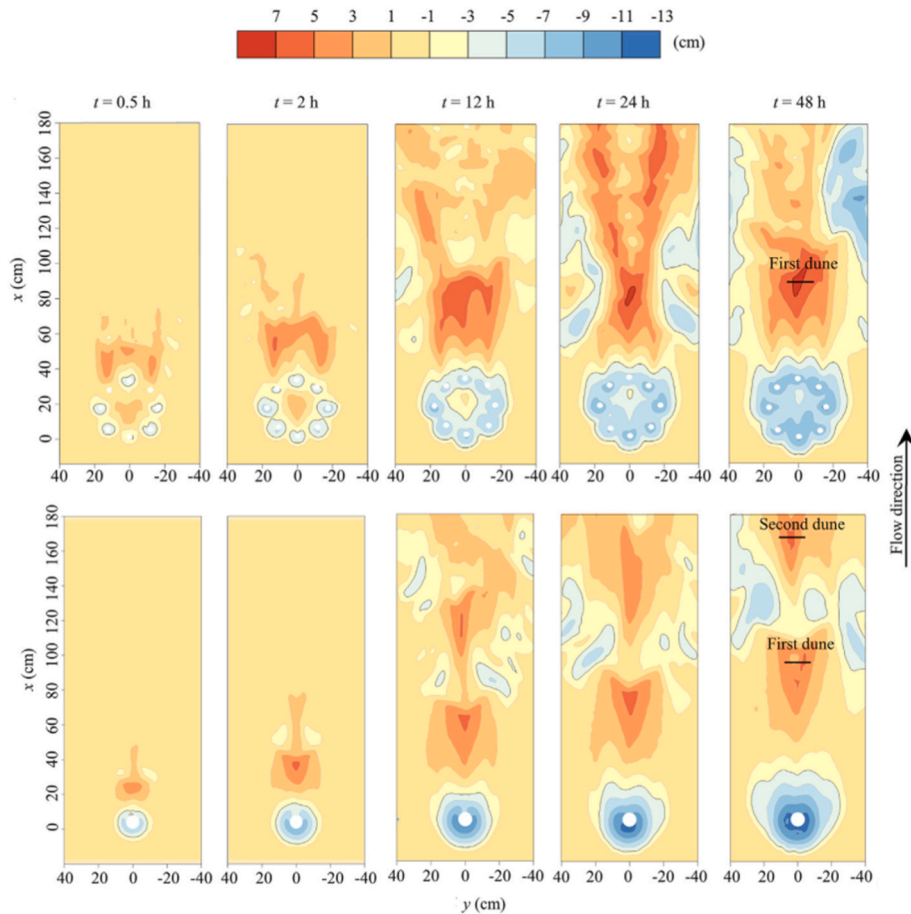


Fig. 19. Scour comparison between a High-Rise Structure Foundation (HRSF) and a Monopile – Reprinted with permission from Xiao et al. (2020), Copyright 2020, Elsevier.

lower blockage ratio generates less scour. Regarding the deposition zone of the sediments, the distance to the foundation changes with the variation of the flow direction.

Although these studies provided valuable information and a good starting point regarding the scour in HRSFs, the fact is they only covered a limited range of conditions (currents). This review shows that a true misrepresentation of in-situ offshore conditions was made, thus highlighting the importance of extending testing conditions for the expansion of the scour protection design to this complex foundation.

3.5. Suction bucket foundations

Suction bucket foundations are skirted structures inserted into the seabed to anchor OWT and offshore platforms of oil and gas, used mainly in the North Sea for clay soils, that do not require seabed preparation and can cover a large range of water depths, from 5 m up to 60 m (Houlsby et al., 2005; Wang et al., 2018).

As monopiles demand an expensive installation, due to the use of heavy pile-driving equipment, this type of foundation offers an economical, simpler, quicker, and non-weather-dependent alternative (Houlsby et al., 2005; Houlsby and Byrne, 2000; Byrne et al., 2002). As the self-weight of the foundation is not enough to thrust the caisson into the seabed, a 'suction' technique, that consists of pumping out the water trapped within the caissons, is used to create a pressure differential across the top of the bucket (Houlsby et al., 2005; Houlsby and Byrne, 2000; Byrne et al., 2002). For cohesive soils, this technique is sufficient to drive the foundation. For sandy soils, the applied suction leads to an upward flow, that reduces the effective shear stress within the caisson, causing a scenario similar to a 'piping failure'. Therefore, the soil-bearing capacity around the rim of the caisson is reduced, allowing it to penetrate the soil (Houlsby et al., 2005; Houlsby and Byrne, 2000; Byrne et al., 2002). Moreover, a suction bucket foundation can be adapted to a variety of bottom-fixed foundations (monopile, jacket, tripods), Fig. 20, and may be removed completely from the seabed, unlike piled foundations (Byrne et al., 2002). The decommissioning and removal procedure is the exact reverse process of the installation, i.e., the application of an overpressure inside the bucket caisson (Houlsby and Byrne, 2000).

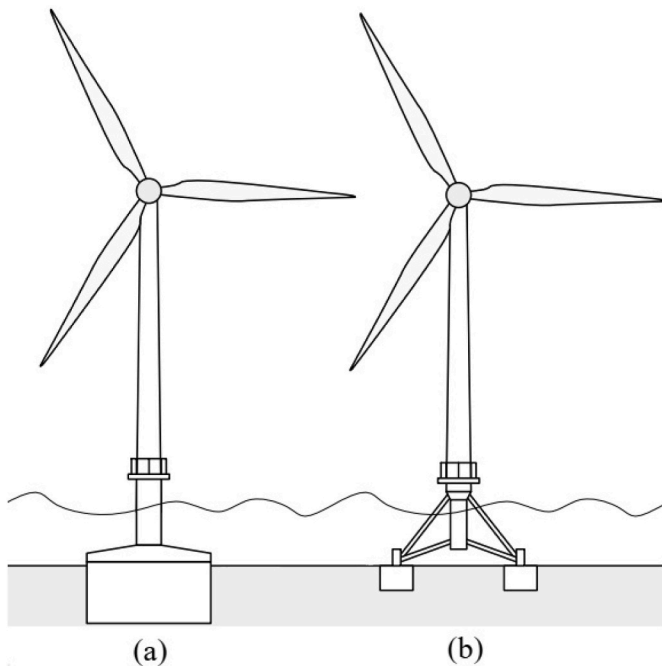


Fig. 20. - Suction bucket foundation for: a) Monopile, b) Tripod - adapted from Houlsby et al. (2005).

In the literature, most studies refer to the structural behaviour, the geotechnical design, or the effects of scour on the ultimate bearing capacity of the caisson that composes the foundation (Houlsby et al., 2005; Wang et al., 2018; Houlsby and Byrne, 2000; Byrne et al., 2002; Sturm, 2017; Guo et al., 2022; Ngo et al., 2023).

Houlsby et al. (2005) mentioned that since part of the suction bucket caisson could remain above the seabed, that could lead to more severe scour conditions. The results of small-scale physical model tests for a monopile bucket foundation, under irregular waves and tidal flows, were compared to the field analysis of decommissioned Horns Rev II and Dogger Bank suction bucket foundations (Stroescu and Frigaard, 2016; Stroescu, 2018). A good agreement between the field measurements (Table 4) and the experimental results (Table A5) was obtained, although the experimental campaign did not simulate the in-situ conditions from the considered sites. The results highlight that a suction bucket foundation could have in fact a lowering effect on scour, due to the blockage effect of the caisson features and due to the backfilling of scour holes registered during in-situ surveys. These observations open the door to the possibility of not including scour protections (Stroescu and Frigaard, 2016; Stroescu, 2018).

Another study regarding scour in a suction bucket foundation was performed by Yu et al. (2019) while testing a composite bucket foundation model under current-only, wave-only, and combined wave-current conditions. The following main conclusions were drawn.

- For the current-only tests, small sediment deposits were formed in front of the model, while scour was detected on both sides of the foundation and at the leeward side of the foundation (two scour "spoon-shaped" pits symmetrically distributed);
- Wave-only tests registered lower scour depths when compared to the currents-only and wave-current tests. As far as the seabed model topography, a strip-shaped deposition area perpendicular to the wave direction was detected 15 cm in front of the foundation. Two scour holes also appeared, one in front of the model, between the caisson and the strip-shaped dune, and the other at the downstream side of the model in the direction of the centre axis;
- For the wave-current tests, scour was detected in front and around the sides of the foundation, causing the exposure of the bucket skirt. A long and narrow scour hole also appeared behind the model, caused by the horseshoe vortex. When compared to the current-only test results, scour depths were lower, but the scour extent was higher;
- Relative scour depth and the horseshoe vortex influence increased with increasing KC values, consistent with scour development at monopile foundations.

As mentioned in Chapter 3.1, a novel foundation was introduced by Welzel et al. (2024), a 6-legged jacket gravity-based suction bucket foundation (Fig. 21). The foundation consists of a jacket with six legs each one with a large container, serving two purposes – offering buoyancy during transportation to the installation site and improving stability by adding weight inside the containers, after installation. To increase the stability even further, the complex foundation is inserted into the seabed using suction buckets. The research aim of Welzel et al. (2024) was to assess the influence of the complex geometric features of the new foundation and compare it to a standard 4-legged jacket. The large containers, due to the large containers, have a substantial blocking effect on the flow, leading to enhanced flow contractions and velocities. The laboratory tests were performed using only currents. For clear-water conditions (Fig. 21) local scour was more prominent than global scour. A

Table 5

Influence of rotor radius on scour for $C/H_r = 0.5$ Sun et al. (2018).

Rotor radius	37.4 mm	45.9 mm	56.3 mm
S/D_{pile}	2.6	2	2.2
Scour relative to a pile ($S/D_{pile} = 1.45$)	+78.9%	+37.5%	+51.3%

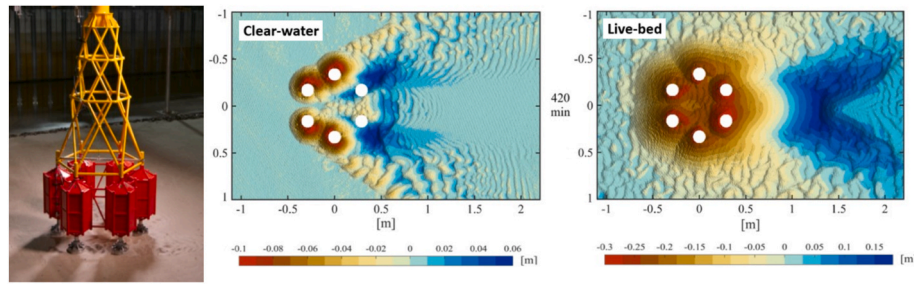


Fig. 21. Scour patterns for a 6-legged jacket gravity-based suction bucket foundation, under clear-water (left) and live-bed conditions (right): Scour – red and orange; Sediment depositions – adapted from [Welzel et al. \(2024\)](#).

maximum scour depth and extent of $0.81D_{caisson}$ and $3.46D_{caisson}$, respectively, was developed around the front and middle piles, while some sediment accumulation around the two downstream piles occurred. For live-bed conditions, the initial local scour holes merged into a singular scour hole and the deposition dune shifted to a distance around $9.8D_{caisson}$ towards downstream of the foundation, similar to the scour pattern around a pile group or even as in HRSFs (Fig. 19). The global scour hole has an extent of $10.8D_{caisson}$, the scour depth at the piles ranges between $2D_{caisson}$ (front and middle) and $2.3D_{caisson}$ (downstream piles), and the maximum scour depth at the centre of the structure is equal to $1.7D_{caisson}$. The results allowed to conclude that.

- For both structures, global scour develops mainly under live-bed conditions. For clear-water conditions, global scour was not intensively observed, an indicator that structural elements and features have little influence;
- Scour development to pile diameter progresses faster in the 4-legged jacket than at the 6-legged jacket gravity based suction bucket foundation;
- For clear-water conditions, the normalized sediment displacement and mean spatial distribution for both foundations were comparable, if the structures' reference diameter and footprint were also normalized;
- For live-bed conditions, spatial scour depth, relative to the 6-legged foundation's footprint, was 2.5 times higher when compared to the standard 4-legged jacket, showing that a significant increase in complexity and blockage ratio of the foundations leads to a non-proportional increase in sediment erosion;
- The local and global scour development at the 6-legged foundation, under live-bed conditions is very much aligned to the scour depths, extent, and shapes observed for an array of piles or even for HRSF;

4. Marine energy converters and hybrid foundations

Nowadays, OWTs and marine harvesting technologies have seen an increasing growth in attention by the private and scientific community

in the marine renewable energy sector.

The energy crisis and climate changes are enhancing the demand, exploration, and investment in hybrid foundations that can combine more than one energy harvesting technology, for example, offshore wind turbines with marine energy converters being in the same foundation or floating platform (Fig. 22). These hybrid systems could optimize and boost power and energy production per structure. The question that arises is whether energy converters could shelter OWTs against waves, currents, and tides, or if they could increase loads, turbulence, and scour mechanisms (downflow, horseshoe, and/or lee-wake vortices) around the foundation.

Most of the new hybrid foundations combine floating OWTs with WECs or TECs. Since this article focuses on complex and hybrid bottom-fixed foundations, other studies are highly recommended for an extensive review of multiple floating hybrid solutions that have been adopted or are still in the development stage ([Saeidtehrani et al., 2022](#); [McTiernan and Sharman, 2020](#); [Taveira-Pinto et al., 2021](#)).

For bottom-fixed hybrid foundations, scour is a topic that has some knowledge gaps ([Fazeres-Ferradosa et al., 2021](#)) and, as it happens in OWT complex foundations, scour protection studies are still non-existent. The main focus has been the study of efficiency and hydrodynamic performance of converters and not so much on the scour behaviour in complex foundations. Nonetheless, scour protections in hybrid foundations remain an important topic of research, since.

- scour represents a threat to the offshore wind structure and the functioning of marine energy converters;
- the eventual accretion of sediments between the converter and the foundation could also lead to an efficiency decrease or malfunctioning of the device, thus reducing its viability;
- the implementation of marine energy converters could lead to softer scour countermeasures, hence reducing costs and expenditures;
- an effective scour protection could optimize the structural behaviour, thus enhancing the usage of hybrid foundations.

The literature points out a large knowledge gap regarding the usage

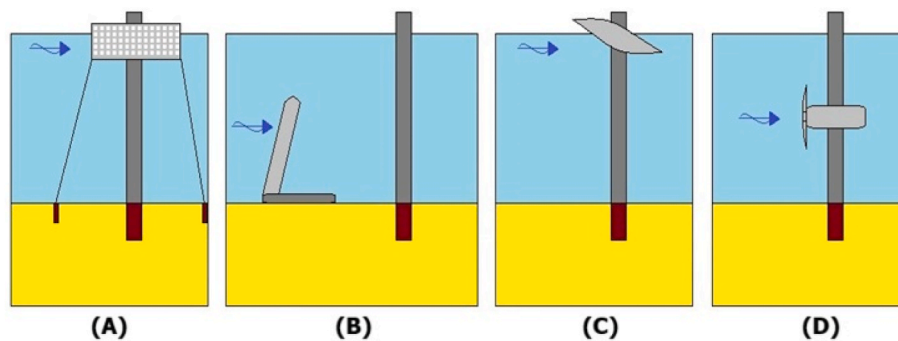


Fig. 22. - Conceptual schemes for possible hybrid OWT foundations, by combining: (A) aquaculture cage, (B) oscillating wave surge converter, (C) wave energy converter, and (D) tidal/current energy converter – not at scale.

and design of scour protections in hybrid foundations.

4.1. Marine energy converters

As aforementioned, the synergy between OWT and marine harvesting technologies presents new challenges and research topics. The movement of an oscillatory/rotative body, causes additional soil-fluid-structure interactions, since wave-orbital and current velocities change, as downflow pressures and vortices, in the vicinity of the structure. Standard scour patterns and behaviour in offshore foundations are no longer applicable. Therefore, scour protections – static or dynamic – designed under the actual knowledge, could be misadjusted.

The assessment of the actual design methods for marine energy converters or hybrid foundations should include other variables, and not just structural parameters (D_{50} , ρ_s , extent, thickness, S/D) and environmental parameters (d , H_s , T_p , U_c , U_m). They should consider cyclical variations of pressure caused by the device movement/oscillation and the influence that vibration increments could have on the natural frequency of the structure. The impact that the converter motion causes in soil properties, disturbance of current and tidal velocities, and variations in the flow field, are also other aspects that could produce some major influences in the design of hybrid foundations and scour protection mechanisms.

4.1.1. Wave energy converters (WECs)

An example of a wave energy converter that enforces a cyclical variation of movement and pressure, is the CECO converter (Rosa-Santos et al., 2019a). By converting its inclined motion into energy, a cycle of upward and downward pressure is started (Fig. 23), interfering with the flow field, enhancing and decreasing velocities, pressures, horseshoe, and lee-wake vortices near the profile bed, mainly behind the foundation (Fazeres-Ferradosa et al., 2021). Moreover, the movement itself could lead to excessive vibratory motion of the pile that supports the WEC. However, there is a possibility that by absorbing and reducing wave heights, the device could reduce scour at the foundation. The uncertainty of those facts would ask for reinforced scour protection or a softer countermeasure, which should be a motive for further exploratory research to assess if both structures – a CECO converter and an offshore foundation – could be advantageous to each other.

Another WEC that could have a positive impact as a scour corrective solution is the Oscillating Wave Surge Energy Converter (OWSEC) similar to a floating plate (Fig. 24), Zhu et al. (2020). This research assessed the implications and viability of such an energy converter as a

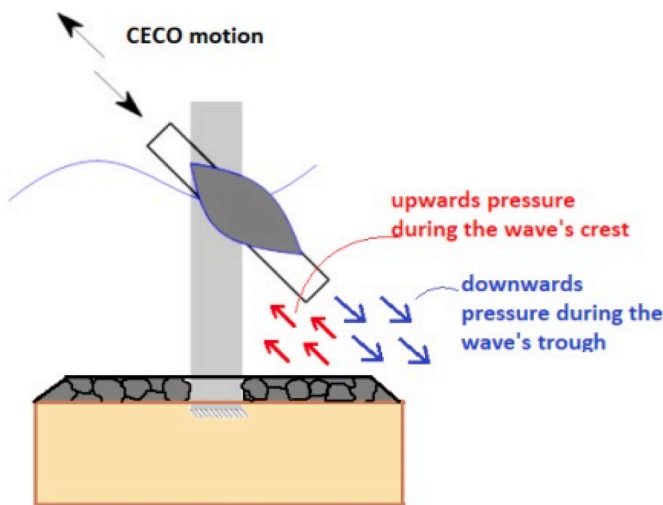


Fig. 23. – Scheme of CECO's movement and expected upward/downward pressure action on a scour protection – adapted from Fazeres-Ferradosa et al. (2021).

protective measure for a pipeline. It concluded that the device could work as a scour-reducing device, depending on characteristics such as size, motion, and other parameters. Thus, the influence of the flap rotation angle (α), wave height-water depth ratio and water depth-wavelength ratio on seabed changes were also studied (Taheri et al., 2022). By performing a set of tests, it was concluded that.

- by changing α , from motionless to a rotational body, scour was reduced in length and range, by moving scouring and deposition zones closer to the structure;
- by increasing α , the flap rotation reduces velocities leading to less scour and more deposition of sediments. But closer to the device, the flap motion and flow disturbances occur and vortices are created, so the scour behaviour is different;
- by increasing the H/d ratio, scour and bed level variations aggravate, concluding that shallow waters or more energetic wave conditions are detrimental to the scour defensive performance of the energy converter.

Therefore, it can be concluded that flap energy converters, when compared to similar fixed structures, decrease scour in the seabed, being a potential good scour countermeasure. However, scour protection might be required to protect the WEC from the problems that may arise from scour in its own foundation.

It should be also worth mentioning that a new floating two-flap OWSEC system (Fig. 25) has been tested by Ruehl et al. (2019), Coe et al. (2020), and Bosma et al. (2016), the so-called Floating Oscillating Surge Wave Energy Converter (FOSWEC). At an initial testing stage, the device was attached to a constraint platform that could lock/unlock different allowable degrees of freedom (DOF), Ruehl et al. (2019) and Bosma et al. (2016). In the second stage, the device was tested using mooring lines (Coe et al., 2020). Loads, the motion of the flaps, platform, and mooring behaviour, power-take-off (PTO) components, and incident wave fields were characterized using irregular/regular wave response tests. The implementation of a similar bottom-fixed version could be an interesting upgrade as a scour countermeasure to single-flap OWSEC.

Oscillating water columns (OWC) have been studied quite extensively in the last few years. Mainly integrated on breakwaters or sea walls, some literature research analysed scour patterns for gravity-based OWC-WEC (Lancaster et al., 2020, 2022). A detailed review of the findings can be seen in Fazeres-Ferradosa et al. (2021). However, the model was updated by adding two lateral pontoons, flap valves, and a chamber flap door (Lancaster et al., 2022). By testing different configurations of the pontoons, and the presence/absence of chamber doors, for different sets of conditions, it was concluded that.

- Even with the presence of the pontoons, scour compromised the back corners of the structure, for all the conditions tested, since downstream scour is regulated by flow contractions and vortex developments;

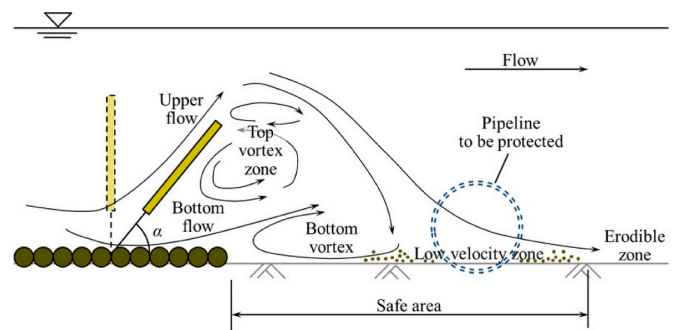


Fig. 24. – Scheme of the working mechanism of a bottom-mounted Oscillating Wave Surge Energy Converter (OWSEC), Zhu et al. (2020).

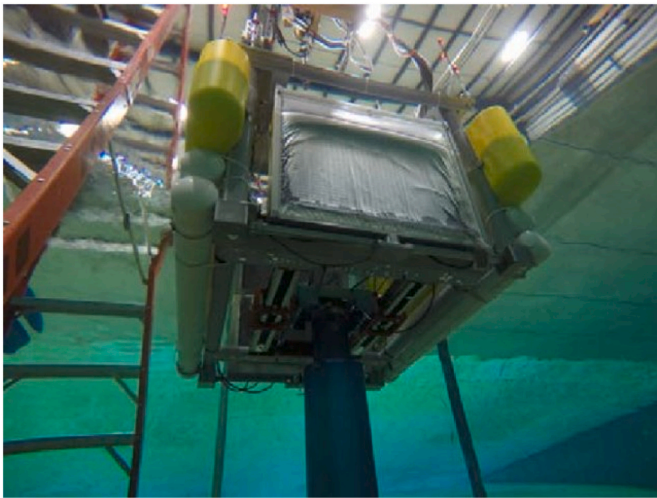


Fig. 25. - Underwater view of the Floating Oscillating Surge Wave Energy Converter (FOSWEC) – (Bosma et al., 2016).

- curve-edged pontoons represented a 23% scour reduction when compared to sharp-edged pontoons;
- the scour hole formation led to settlements of the structure.

These findings indicate that a hydrodynamic structural improvement of energy converters and offshore foundations could decrease scour in their vicinity, leading to the need for new, softer scour protective measures. Moreover, both studies advise some form of seabed preparation or scour protection to prevent settlements. These observations are aligned with the conclusions drawn in Van Velzen et al. (2016). Van Velzen and Bruinsma (2017), and Bruinsma et al. (2018).

4.1.2. Tidal current energy converters (TECs)

As WECs have shown to be a viable option to reduce scour when combined with OWT. TECs, on the other hand, represent a meaningful challenge since they induce some effects – the rotor may block the flow causing acceleration in current velocities, the wake effect of the turbine may alter hydrodynamics, and the enhanced turbulence could increase shear stress at the seabed vicinity –, thus enhancing scour around the structure (Chen and Lam, 2014; Kang et al., 2012; Neill et al., 2009). However, scour protection studies in TECs are non-existent to the authors' knowledge, but there is some information on scour in TECs, based mainly on the experience with ships' propellers or turbines fixed on single piles.

The rotor's effect, the increased wake effect under the turbine, and the tip clearance – the distance between the tip of a rotating blade to a stationary part, point, or object – are pointed out as the main considerations for scour induced by TECs (Chen and Lam, 2014). These facts are reinforced by Chen et al. (2017), which studied the influence of tip clearance on scour for a pile-supported horizontal axis turbine. The rotative movement of turbines has been proven to increase local velocities downflow, and the occurrence of horseshoe vortices, causing an amplification of shear stresses (Chen et al., 2017; Hill et al., 2014; Sun et al., 2018). By comparing three different tip clearance distances, results showed that lower distances to the bed profile lead to a faster scour extent of up to $1D_t$ downstream, and $0.5D_t$ from both sides (Chen et al., 2017).

A similar research on a Darrieus-type vertical axis turbine to assess scour parameters was developed for different tip clearance distances but also for distinct turbine radius (Sun et al., 2018). The results were in line with Chen et al. (2017), as the decrease in the tip clearance also led to higher scour rates – a 10%–20% increase in scour extent, and a 30% increase in scour depth. Moreover, it was concluded that equilibrium scour is independent of tip clearance, since a continuous decrease of the

distance to the sediment bed, at a certain point, does not translate to a significant increase in scour depth – the live bed scour effect takes control.

Considering the influence of the rotor radius, it was concluded that with the radius increment, maximum scour depths decrease at first and then increase (Sun et al., 2018) – Table 5; as for the tip clearance, scour increases in depth and extent with the decrease of the parameter (Table 6).

The maximum scour depth was achieved for a small rotor radius and when $C/H_r = 0.5$ – tip clearance distance (C), the height of the turbine rotor (H_r), Sun et al. (2018). As for the minimum scour ($1.6D$), it was obtained for the maximum rotor radius when the distance to the bed was equal to the height of the rotor. This is an indication that to minimize the prejudicial effect that TECs have on scour, the inclusion of these devices on OWT should be placed at a relatively high distance from the seabed.

The performance analysis of TECs by Chen et al. (2017) and Sun et al. (2018) was only carried out under currents. The results presented in Table 5 proved that tidal current devices can be detrimental to offshore foundations, reinforcing the idea and necessity of scour protections (Chen et al., 2013). The empirical formulas to predict scour in tidal current turbines (Chen et al., 2017; Sun et al., 2018), are a good starting point to build new proposals for scour protections for TECs.

A scour reduction using a tidal current turbine (TCT) was assessed by Charlier (2003) when implemented at an optimal position in front of a monopile facing the currents. In addition to reducing shear stress, the device also reduced the maximum depth of scour. It was indicated that scour evolves slower and is amplified further away from the rotor when the device is placed downstream of the foundation (Hill et al., 2014). This evidence was also detected by Yang et al. (2021) when using a numerical and physical model of a TCT on the sea-side of a monopile (1:12 scale factor). By varying the distance of the TCT to the foundation (10–50 cm) and the tip clearance distance to the seabed (5–25 cm), Fig. 26, for the same rotor speed and current velocity, it concluded that the device had the potential of reducing scour around the foundation (mainly in front and on both sides of the monopile). When properly installed, with an optimal distance of 30 cm to the turbine and 10 cm to the seabed, the TCT reduced the maximum shear stress on the seabed by 8% and the maximum scour depth by 42%. However, when placed closer or further away from this optimal position, scour depths and shear stresses reached similar rates to the control model (without the use of the converter). Hence, Yang et al. (2021) highlights that the scour mitigation effects of this type of device is highly conditioned to its installation position, to the tidal current speed, and to the rotor speed. Therefore, the author suggests that the implementation of such device in an OWT foundation should be done by carefully selecting its rotational speed and position taking into consideration different tidal current conditions.

These opposite opinions enhance the necessity to perform further research to clarify some contradictions and to ensure that scour protections can be accounted for in the optimization of tidal current energy converters.

4.2. Hybrid foundations

In literature, it is found the inclusion of WECs in maritime structures such as breakwaters, sea walls, and harbours, among others. It was concluded that for the toe region, erosion and sediment transport due to

Table 6

Influence of the tip clearance on scour for the same rotor radius ($H_r = 56.3$ mm), Sun et al. (2018).

C/H_r	1.00	0.75	0.50	0.25
S/D_{pile}	1.6	1.7	2.2	2.2
Scour relative to a pile ($S/D_{pile} = 1.45$)	+9.9%	+16.8%	+51.3%	+51.3%
Scour extent (downstream)	4.6D	4.8D	8.5D	10.0D

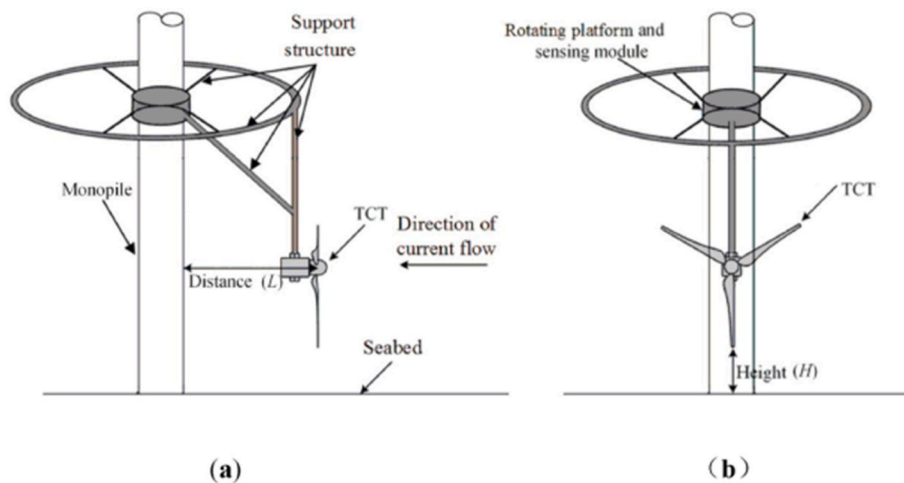


Fig. 26. Three-bladed TCT device: (a) side view, (b) front view – Reprinted with permission from Yang et al. (2021), Copyright 2020, Elsevier.

wave reflection, breaking, and splashing is increased (Mustapa et al., 2017). Therefore, countermeasures against scour in these types of structures are necessary.

A model of a hybrid system by integrating a WEC into a rubble-mound breakwater to assess the stability under extreme onshore conditions was performed by Rosa-Santos et al. (2019b). Although no scour was detected at the end of 6000 waves, despite some block movements at the toe, Rosa-Santos et al. (2019b) looked for potential scour at the structure by including an energy converter.

Nevertheless, a soft scour countermeasure by adding a coastal cage net for aquaculture on an offshore jacket was implemented (Hsin-Hung et al., 2014). The concept of offshore aquaculture has been developed in the last few years and has gained a lot of momentum. The conclusions drawn help prevent scour around the foundation. For a 100-year return period wave-current condition, the maximum scour depth was reduced from $1.17D$ (without the cage) to $0.75D$ and $0.71D$ – one cage at the current side and one net at the current side and another at the wave side, respectively – representing a 35%–39% scour depth reduction (Hsin-Hung et al., 2014).

A combination of an OWSEC with an OWT foundation (monopile and GBF), under waves and currents for layered soils was used to assess scour by Miranda (2022). The study integrated the device at the upstream side of the foundations (Fig. 27). For a set of conditions (Table A6), the converter was placed at further distances from both foundations. The results obtained were compared to a setup without the device. A 16 set of tests for a geometrical scale of 1:50 resulted in Table A6.

Overall, several results reported an average reduction of the scour depth – 60% and 33% for the monopile and GBF, respectively – obtained with the presence of the wave flap energy converter in front of both foundations for a fine sand seabed (Miranda, 2022). As for layered soil, a decrease of 65% (monopile) and 67% (GBF) on the scour depth was registered. Even though scour protection was not incorporated, the values suggest that this approach could and should be considered as a scour countermeasure. It seems to be viable and could lead to the implementation of less extensive and thicker riprap protection, reinforcing that static protections may not be necessary, leading to considerable cost reductions.

Furthermore, Miranda (2022) states that:

- for the monopile, scour depth presented a higher value for fine sand instead of for the layered soil, without the device. With the presence of the WEC, that difference between scour depth for fine sand and layered soil was dissipated;

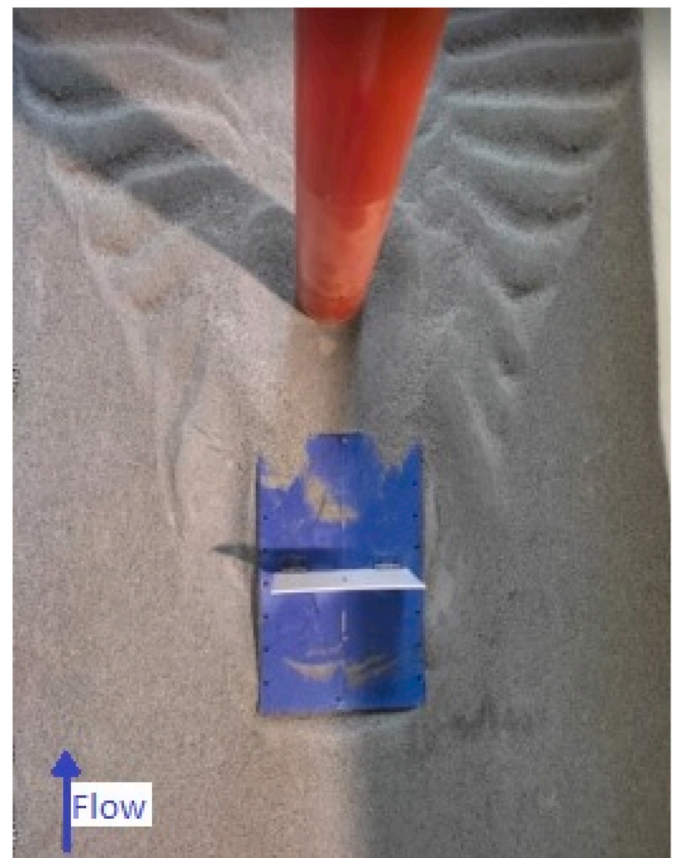


Fig. 27. Monopile and Oscillating Wave Surge Energy Converter (OWSEC) tested by Miranda (2022).

- for the GBF, without the OWSEC, the scour depth for both soils was similar. As a result of implementing the device, the layered soil experienced lower values of scour.

As a result of these findings, it is suggested that each case should be evaluated individually. To mitigate the differences in scour depth for each foundation in each soil combination, scour protections can play a significant role.

In summary, the literature shows a clear lack of research on scour protections for marine harvesting technologies and hybrid foundations.

Those subjects need to be properly addressed to optimize the design and implementation of these structures. The understanding of each specific interaction that those devices have between each other and with the seabed is fundamental. Depending on the offshore environmental conditions, certain energy converters may increase or decrease scour around such structures. The comprehension of scour phenomena when energy converters are applied could lead to novel concepts of scour protection, essential to the preservation of the structure. Since cost expenditures are still the decisive variable in the implementation of such alternatives, each energy converter needs to be addressed individually in the design initial stage. A future correct combination of energy converter-OWT foundation-scour protection can lead in fact to a significant cost reduction and improvement of the foundation's stability and competitiveness of offshore renewables.

5. Conclusions

This article aims to review the latest outcomes of the scour phenomena and protections related to the presence of offshore and marine harvesting technologies, to summarize the most recent knowledge gaps and research performed namely on offshore wind turbine foundations, with a special focus on complex and hybrid bottom-fixed foundations. Several challenges and potential future developments were identified, as a brief analysis of the most recent developments on scour protections for OWT. It was intended to show that the different topics here listed can support and serve as a basis for upcoming research, development, and optimization of scour protections for complex and hybrid OWT foundations in a marine environment, possibly leading to lower costs and higher performances of offshore and marine harvesting technologies.

From this review, the following conclusions can be presented.

- The study of scour around monopiles has been extensively covered in the literature. In recent years, the discussion regarding scour on complex bottom-fixed foundations has grown, still, some of the approaches used in actual situations are monopile-related. There is a need for further understanding, as higher global and local scour depths were detected in complex structures when compared to the average monopile scour depth (Welzel, 2021);
- There is a lack of a general understanding of the scour development at complex structures. Most studies only analyse the evolution of equilibrium/maximum scour depths, thus neglecting a deeper analysis of the time scale, spatial scour depth variations, erosion/deposition patterns, the interaction between local and global scour, and the influence of the complex structural design features on the spatial scour depth changes;
- The prediction of scour effects frequently relies on simplified hydraulic conditions, waves and/or currents. There is a lack of knowledge on the effects of real hydraulic conditions, such as the simulation of tidal flow conditions or the influence of multidirectional waves, on the scouring process;
- Traditionally, static scour protections are the most utilized and studied type of protection, despite being based on some sort of empirical concepts. Less expensive optimizations, such as dynamic or wide-graded alternatives, are not fully developed or studied, at the same level of knowledge, nor have been extensively addressed for complex foundations, marine energy converters, and hybrid foundations;
- Design formulas heavily based on monopiles are still used or adapted, even though scour behaviour, flow field modifications, blockage effects, and loads around complex structures are different;
- The scour protection stability assessment is a crucial part of the design procedure. Nonetheless, only a few studies have focused on major improvements regarding the stability evaluation, damage characterization, and the scale effects associated with the application of small-scale physical model tests;
- Absence of access to data, result discussions, reports, and information in situ, that are retained by stakeholders, due to confidential policies, harms the development or optimization of (new) scour protection design formulas;
- Although the number of studies that have used numerical models has been increasing in recent years, scour protection numerical models are still a huge field of study yet to be covered. The majority of the models focus on the structural behaviour of bottom-fixed or floating foundations;
- Most studies regarding marine harvesting technologies focus on hydrodynamics and performance improvement over scour and protections. No studies are reporting the use of scour protections, and scour research considers only waves for WECs or tidal currents for TECs, a miss-representation of real marine environmental conditions;
- Scour studies in hybrid structures are scarce and almost non-existent, even with the high potential that the application of energy converters in offshore wind turbines can offer. A synergy between both could contribute to a cost reduction, to the creation of new energy sources that in the end could increase the competitiveness of the renewable energy sector and devote to the reduction of the electricity price;
- Knowledge gaps and lack of reports in the literature on the combination of WECs or TECs with OWTs can lead to the increase or reduction of scour effects in the foundation.

As a final note, there is a clear absence of works that performed physical and numerical modelling of scour protections for complex and hybrid bottom-fixed foundations, and marine harvesting technologies. Although some encouragements have been made regarding the understanding of scour development and prediction formulas on OWT complex foundations and marine energy converters, the authors recognize that the future of scour research in the offshore sector involves the necessity of identifying new and specific design formulas and counter-measures for (dynamic) scour protections for these types of foundations and structures.

CRediT authorship contribution statement

J. Chambel: Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Conceptualization. **T. Fazerres-Ferradosa:** Methodology, Conceptualization, Project administration, Writing – original draft, Writing – review & editing. **F. Miranda:** Writing – review & editing. **A.M. Bento:** Writing – review & editing. **F. Taveira-Pinto:** Project administration, Writing – review & editing. **P. Lomonaco:** Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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Abbreviations

A	Reference distance times the structure footprint length
A_{front}	Reference distance relative to the structure's upstream side
A_{rear}	Reference distance relative to the structure's downstream side
A'	Equation (8) additional term
a_0, a_2, a_3	Regression fitting coefficients
a_1, a_4	Coefficient for hydrodynamic conditions
B	Jacket lowest node distance impact coefficient
B'	Equation (7) additional term
B''	Equation (8) additional term
b_0	Regression fitting coefficient
C	Tip clearance distance
C'	Equation (7) additional term
c_1, c_2, c_3	Equation (11) regression fitting coefficients
D	Diameter
D^*	Dimensionless grain size
D_{caisson}	Suction bucket caisson diameter
D_{cr}	Critical stone size
D_{base}	Diameter of a non-uniform cylindrical structure
D_e	Equivalent diameter
D_{n50}	Nominal stone diameter of the scour protection
D_p	Pile diameter
D_t	Turbine disc diameter
D_{15}	15th percentile of scour protection material grading
D_{50}	Mean stone diameter of the scour protection material
$D_{67.5}$	67.5th percentile of scour protection material grading
D_{85}	85th percentile of scour protection material grading
d	Water depth
d_p	Diameter HRSF individual piles
d_s	Local scour depth for HRSF piles
d_{se}	Equilibrium scour depth for HRSF individual piles
Eu	Euler number
Fr	Froude number
G	Pile gap
g	Gravitational acceleration
H	Wave height
H_m	Mean wave height
H_{m0}	Spectral significant wave height
H_r	Height of turbine rotor
H_s	Significant wave height
h	flow depth
KC	Keulegan-Carpenter number
k	wave number
kw	GSC volume factor
k_1	Velocity correlation factor
k'	HRSF location constant
l	GSC long edge length
N	Number of waves
N_s	Stability number
N_s^*	Modified stability number
n	Number of HRSF piles
R	Protective strength ratio
Re_D	Structure Reynolds number
R'	Radial distance of the scour hole
S	Scour depth
S/D	Relative scour depth
S/D_{column}	Maximum relative scour depth under the column
S/D_{pile}	Maximum relative scour depth in the piles
S_{3D}	Damage number
S_{currents}	Equilibrium Scour depth under current-only

S_{eq}	Equilibrium scour depth
S_{end}/D	Relative maximum scour depth
S_{max}/D	Relative maximum scour depth at GBS's pontoons
s	specific density (ρ_s/ρ_w)
T	Wave period
T^*	Dimensionless time scale
T_c	Time scale period
T_e	Equilibrium time scale for HRSF
T_m	Mean wave period
$T_{m-1,0}$	Energy wave period
T_p	Wave peak period
t	time step in scour process for HRSF
U_c	Depth averaged current velocity
U_{cr}	Mean threshold velocity of sediments
U_{cw}	Velocity ratio
U_m	Orbital bottom velocity
U_{max}	Vortice local maximum velocity
V	GSC volume
$V_{A,i}$	Cumulative erosion volume
$V_{A,max}$	Maximum erosion volume
V_{Area}	Areal development of volumes
V_c	Threshold sediment motion velocity
V_s	Scour Volume for HRSF
V_{se}	Equilibrium scour volume for HRSF
W	GSC weight
w_s	Settling velocity
α	Flap rotation angle
α_f	Amplification factor
α_{wc-mp}	Interaction angle between wave-current load and ACM-pipeline system
ζ	Function of hydrodynamic conditions
θ_{cr}	Critical Shields parameter
ρ	Density of the GSC
ρ_s	Density of rock material
ρ_w	Water mass density
τ_{cr}	Critical bed shear stress
τ_m	Mean combined bed shear stress (current and wave-induced)
τ_{max}	Maximum combined bed shear stress (current and wave-induced)
γ	GSC specific weight
Δ	Buoyant GSC density

Appendix A. Complex and Hybrid Foundations Physical Model Studies (Tables)

Table A.1

Physical modelling studies for jackets' scour protections – prototype values.

Reference	Sarmiento et al. (2021)	Bruinsma et al. (2018)	Hsin-Hung et al. (2014)
Scale	1:30	Full Scale	1:36
d (m)	39.93	[30.00, 32.30]	[12.00, 16.00]
T_p (s)	Not provided	[0.00, 12.50]	[7.00–11.74]
U_c (m/s)	50-year Return Period (exact value not provided)	[0.00, 1.20]	[0.00, 1.00]
Types of Waves	Irregular	Irregular	Irregular
H_s (m)	[1–50] year Return Period (exact value not provided)	[0.00, 8.90]	[2.50–7.72]
Duration	3 h (18 h cumulative)	Not provided	8 h
Wave-Current Direction	0°	Not provided	90°
D (m)	Not provided	Not provided	4-pile jacket (2.08 m diameter/pile)
Protection type	Riprap	Riprap	Riprap + Precast concrete blocks
D_{n50} (mm)	Not provided	[76.2–228.6]	Not provided
ρ_s (kg/m ³)	Not provided	3050	Not provided
Armour Thickness	Variable (but up to $5D_{50}$)	1 m	3 m (2 m embedded in the seabed)
Armour Extent	Not provided	12 m radius from each pile (square protection)	14 m radius from each pile (square protection)
Filter	–	–	Geotextile & Granular

Table A.2

Physical models and in-situ scour analysis for tripods – prototype values.

Reference	Stahlmann and Schlurmann (2010)		
Scale	1:40	1:12	1:1
d (m)	[24, 30]	30	28
T_p (s)	[9.5–19.0]	[9.6–19.1]	In-situ measurements Conditions (50-year period): Waves: $H_{s,50} = 8.5$ m, $H_{\max,50} = 15.8$ m, $T_{p,50} = 12.3$ s Currents: $U_{c,50} = 1.3$ m/s, $U_{c,ground50} = 0.8$ m/s
Types of Waves	Regular + Irregular	Regular + Irregular	
H_s (m)	[4–12]	[6.12–9.24]	
Duration	[3000 to 6000] waves	[2500, 3000, 4000] waves	
D (m)	Not provided	Not provided	Not provided
S/D (Rear pile 1)	0.66	1.05	[1.1–1.4]
S/D (Rear pile 2)	0.67	1.03	
S/D (Front pile)	0.55	0.80	
S/D (under Main Columns)	–	1.11	2.5
S/D (Downstream)	0.92	0.31	–

Table A.3

Physical modelling studies for GBFs' scour protections – prototype values.

Reference	Wilms et al. (2012)	De Sonnevile et al. (2014)	Chen et al. (2011)	Tavouktsoglou (2018)	Gao et al. (2023)
Scale	1:17	1:60	1:50	1:100	1:100
d (m)	37.5	[28.2, 29.3]	29	40	30
T_p (s)	13.8	[0.0–13.6]	Bora: 9.9 Scirocco: 12.0	[10.0–30.0]	[8.0–12.0]
U_c (m/s)	–	[0.30–2.00]	Normal direction: Bora: 0.53 Scirocco: 0.10 Inline direction: Bora: 0.07 Scirocco: 0.18	[-2.9 – 6.5]	[1.5–2.5]
Types of Waves	Irregular	Irregular	Irregular	Regular	Regular
H_s (m)	10.8	[0.0–10.0]	Bora: 5.3 Scirocco: 5.9	[0.0–16.0]	[5.5–8.5]
Duration	5000 waves	2000 waves 15.5 h (only currents)	18 h	10 000 waves 5 h (only currents)	3 h
Wave-Current Direction	–	0°	Bora: 60°	[0°, 90°]	Waves or Currents: [0°, 90°]
D (m)	32.5	Bidirectional 90 × 70 (rectangular)	Scirocco: 150° Main Structure: 88 × 180 (rectangular) Mooring Dolphins: 56.4 × 28.4 (rectangular)	20	Main Structure: 70 × 90 (rectangular)
Protection type	Geotextile sand containers	Riprap	Riprap	Riprap	6 different systems
D_{n50} (mm)	Container: 2.05 m × 2.05 m	[250, 360, 420]	Not provided	[294, 546, 882]	760
ρ_s (kg/m ³)	Not provided	[2650, 3200]	Not provided	[2500, 2550, 2620]	1700
Armour Thickness	2 layers	5D _{n50} (initial) Varying (final)	Varying	Not provided	2.5D ₅₀
Armour Extent	52.5 m (diameter)	118 m × 98 m (initial) Varying (final)	Varying	5D	1.25 to 1.5D
Filter	Not used	Granular (D ₅₀ = 0.05 m)	Not used	Geotextile	Varying

Table A.4

Physical modelling studies for scour in HRSFs – prototype values.

Reference	Xiao et al. (2020)	Xiao et al. (2021)	Liang et al. (2021)
Scale	1:50	1:50	1:50
d (m)	7.5	[7.5, 12.5]	[5–12.5]
U_c (m/s)	1.96	[1.63–1.98]	[1.91–2.05]
Duration (model)	48 h	100 h	96 h
Current/Alignment angle	[0–22.55] °	[0–22.55] °	0°
D_p and D_c (m)	Monopile: 4 m 8-pile HRSF: 4.95 m 10-pile HRSF: 4.75 m	Monopile: 4 m 8-pile HRSF: 4.95 m 10-pile HRSF: 4.75 m	10-pile HRSF: 4.75 m
Bottom outer diameter (m)	Monopile: 4 m HRSF: 17 m	Monopile: 4 m HRSF: 17 m	HRSF: 17 m
S/D or S/D_e	Monopile: 1.56 8-pile HRSF: [0.96–0.98] 10-pile HRSF: [0.99–1.01]	Monopile: [0.45–1.71] 8-pile HRSF: [0.52–1.14] 10-pile HRSF: [0.48–1.10]	≈1.05

Table A.5
Physical modelling studies for Suction Bucket foundations – prototype values.

Reference	Yu et al. (2019)	Stroescu and Frigaard (2016), Stroescu (2018)	Welzel et al. (2024)
Scale	1:40 1:60	1:90	1:45
d (m)	[8, 10]	28.8	30.2
T_p (s)	[6.64–7.98]	[11.48–12.24]	–
U_c (m/s)	[1.11–1.27]	[1.71–3.98]	[1.61, 2.817]
Type of waves	Irregular	Irregular	–
H_s (m)	[1.2–2.4]	[4.5–9.0]	–
Duration (model)	Currents-only: 24 h Waves-only: 21 h Waves-Currents: 32 h	2 h	Currents-only: 7 h
Wave-Current direction	0°	[0, 90] °	currents-only: 0° (unidirectional)
$D_{caisson}$ (m)	30	18	5.85
S/D _{caisson}	Currents-only: [0.069, 0.134] Waves-only: 0.055 Waves-Currents: [0.066–0.144]	[0.05–0.4]	Clear-water regime: 0.81 Live-bed regime: [2–2.3]

Table A.6
Physical modelling study for a hybrid monopile & GBF foundation (Miranda, 2022) – prototype values.

Type of soil	Fine sand bed	Layered soil
Scale	1:50	
d (m)	18	
T_p (s)	[9.31–10.27]	[9.31–10.35]
U_c (m/s)	1.22	
Type of Waves	Irregular	
H_{m0} (m)	[4.65–5.1]	[4.4–4.85]
U_m (m/s)	[0.785–0.919]	[0.757–0.898]
U_{cw}	[0.570–0.608]	[0.575–0.616]
Duration	3000 waves	
Wave-current direction	0°	
D (m)	Monopile: 5.5 GBF: 9	
Converter	OWSEC: 7.5 m × 5 m flap	
Converter distance to the foundation	[7.5, 12.5, 17.5] m	
$S_{monopile}$	No WEC: 1.65 m WEC: [0.65–0.75] m	No WEC: 2.5 m WEC: [0.65–0.9] m
$S/D_{monopile}$	No WEC: 0.30 WEC: [0.12–0.14]	No WEC: 0.45 WEC: [0.12–0.16]
S_{GBF}	No WEC: 0.8 m WEC: [0.5–0.55] m	No WEC: 0.9 m WEC: [0.15–0.45] m
S/D_{GBF}	No WEC: 0.09 WEC: 0.06	No WEC: 0.10 WEC: [0.02–0.04]
Scour protection	Not applied	

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Appendix III – Chambel *et al.* (2025)

Article

Comparative Analysis of Scour in Riprap-Protected Monopiles and Hybrid Foundations

João Chambel ^{1,2,*} , Tiago Fazerer-Ferradosa ^{1,2} , Mario Welzel ³, Francisco Taveira-Pinto ^{1,2} and Pedro Lomónaco ⁴ 

- ¹ Department of Civil Engineering and Georesources, Faculty of Engineering, University of Porto (FEUP), Rua Dr. Roberto Frias s/n, 4200-465 Porto, Portugal; tferradosa@fe.up.pt (T.F.-F.); fpinto@fe.up.pt (F.T.-P.)
- ² Marine Energy and Hydraulic Structures Research Group, Interdisciplinary Center of Marine and Environmental Research (CIIMAR-LA), University of Porto, Port of Leixões Cruise Terminal, Av. General Norton de Matos s/n, 4450-208 Matosinhos, Portugal
- ³ Ludwig-Franzius-Institute for Hydraulic, Estuarine, and Coastal Engineering, Leibniz University Hannover, 30167 Hannover, Germany; welzel@lufi.uni-hannover.de
- ⁴ O.H. Hinsdale Wave Research Laboratory, College of Engineering, Oregon State University (OSU), Corvallis, OR 97331, USA; pedro.lomonaco@oregonstate.edu
- * Correspondence: up201304674@fe.up.pt

Abstract

As the demand for new sustainable solutions for harvesting energy increases, the offshore energy sector focuses on optimising well-established state-of-the-art solutions while striving for new innovative approaches. Hybrid foundation designs have introduced new challenges and raised questions regarding scour and effective countermeasures. To further improve the knowledge regarding scour prediction, this paper presents and analyses the results from an experimental study behaviour of a riprap protection system for a monopile that determines and characterises scour on a flexible arrangement of overlapping sub-areas. The study was complemented by a novel series of tests using a hybrid foundation, where an oscillating surge wave energy converter (OSWEC) type was coupled to the monopile. Despite being submitted to similar hydrodynamic conditions, distinct differences in the scour rate and damage number (S_{3D}) were observed for both models. Although the OSWEC type contributed to local wave height attenuation (up to a 30% reduction on the leeward side of the hybrid monopile), its oscillatory motion severely aggravated scour, with measured damage rates two to three times higher than those observed in isolated monopiles. These results raise relevant questions about the applicability of existing design formulas for scour protection and underscore the necessity for revised criteria tailored to hybrid offshore foundations.

Keywords: offshore renewable energy; scour protection; monopiles; wave energy converter; hybrid foundations



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1. Introduction

1.1. Background

Offshore wind energy research has grown rapidly, becoming a key component of a global renewable energy strategies. The structural integrity and long-term stability of offshore wind turbine (OWT) foundations, predominantly using monopiles [1], are critical for ensuring economic feasibility and safety. A primary concern regarding the stability of the foundation, which entails around one-third of the overall investment [2,3], is scour, a

common cause of interference in bearing capacity, the ultimate, and service limit states [4,5]. Various countermeasures, such as riprap protections, represent an essential part of that investment [6] and are commonly installed at the base of these structures to mitigate scour-related challenges. Implementing these countermeasures follows established empirical guidelines [7]. Existing design formulas and approaches are commonly monopile-related, creating a lack of a general understanding of scour development at more complex structures, such as jackets, gravity-based foundations (GBF), tripods, or even hybrid foundations [8]. The concept of hybrid energy solutions, i.e., the co-location of wave energy converters (WEC) with offshore wind foundations, has developed increasing interest from the scientific community and the private sector. Enhancing energy yield and optimising spatial utilisation of marine areas could help lower the levelised energy cost (LCoE). It remains unclear to what extent sediment mobilization and altered flow patterns caused by hybrid monopile structures impact the marine environment both near the foundation and in the far field. While WECs are designed to extract energy from waves, their presence can modify in-depth hydrodynamics, wave propagation, current patterns, turbulence levels, and scour mechanisms (downflow, horseshoe, and/or lee-wake vortices) around the foundation. Understanding the impact of these changes on the performance and stability of existing scour protections is crucial for a safe and efficient deployment of hybrid offshore energy systems.

Several authors have studied the effectiveness and behaviour of riprap protections, inspired by rubble-mound breakwaters. This type of countermeasure is widely used due to its low cost and material availability, although transport and installation costs may vary with the location, armour layer thickness, and required stone size [9,10], among other aspects.

1.2. Scour Protections: Design

The threshold of motion concept by [11], was one of the first studies providing insights into scour and scour protection design. This type of protection was later classified as static by [7,12] since the movement of the elements of the armour layer is not allowed. Hence, the median stone size (D_{50}) should be determined so the shear stress induced by the offshore conditions is smaller than the critical shear stress (τ_{cr}) of the rock material—Equation (1), where ρ_s is the mass density of the material, ρ_w is the water mass density, θ_{cr} is the critical Shields parameter, which for non-cohesive soils is given by Equation (2), and is dependent on the dimensionless grain size (D^*), Equation (3), where ν is the kinematic viscosity of water. For $D^* > 100$ on non-cohesive soils, θ_{cr} has the asymptotic value of 0.056.

$$\tau_{cr} = \theta_{cr} g (\rho_s - \rho_w) D_{50} \quad (1)$$

$$\theta_{cr} = \frac{0.3}{1 + 1.2D^*} + 0.055(1 - \exp[-0.02D^*]) \quad (2)$$

$$D^* = D_{50} \left(\frac{g(s-1)}{\nu^2} \right)^{1/3} \quad (3)$$

An amplification factor (α) for monopiles should reflect the foundation's effect on enhancing the flow conditions and the associated shear stress [13,14]. An alternative way to obtain the maximum wave-and-current-induced shear stress for wide graded protections was provided by [15], but the formula uses the $D_{67.5}$ value for a $\theta_{cr} = 0.035$, instead of D_{50} .

The conservative approach of static design led to expensive solutions, given the larger stone size applied, but it is the most common type of countermeasure used in commercial offshore wind projects [9,10]. An optimisation was introduced by [12] in the OPTI-PILE project, the concept of dynamic protection, which allowed for the controlled movement of the armour layer elements, thus reducing both the size, thickness, and volume of the material needed [2]. This new approach, [12], proposed a stability parameter (stab),

Equation (4), where $\theta_{\max}$ is the maximum dimensionless wave–current-induced shear stress. The threshold of motion ceases to be the design criterion, and [12] defines failure when the filter layer is exposed to an area equivalent to $4D_{n50}^2$ —an area equivalent to a square of two-by-two stones of D_{n50} .

$$stab = \theta_{\max}/\theta_{cr} \quad (4)$$

Nonetheless, the stab parameter was still dependent on the amplification factor, whose values differ from author to author and cannot be extrapolated to more complex structures [8,9]. Therefore, the three-dimensional damage number (S_{3D}) for scour protection was introduced by [7,16], based on the concept of the two-dimensional number [17]. By performing an extensive physical model study, it was noted that the stab parameter failed to predict some of the motion caused under different hydrodynamic conditions. The advantage of the proposed S_{3D} , Equation (5), was that it is not dependent on the critical shear stress or the amplification factor, leaving behind some of the limitations of the considerations presented by [11,12,15], allowing a classification of the protection into three different levels of damage: static ($S_{3D} < 0.25$), dynamic ($0.25 < S_{3D} < 1.00$), and failure ($S_{3D} \geq 1.00$):

$$\frac{S_{3D}}{N^{b_0}} = a_0 \frac{U_m^3 T_{m-1,0}^2}{\sqrt{gd}(s-1)^{3/2} D_{n50}^2} + a_1 \left(a_2 + a_3 \frac{(U_c/w_s)^2 (U_c + a_4 U_m)^2 \sqrt{d}}{g D_{n50}^{3/2}} \right) \quad (5)$$

where N is the number of waves, g is the gravitational acceleration, d is the water depth, U_m is the orbital velocity, $T_{m-1,0}$ is the energy wave period, s is the ratio between ρ_s and ρ_w , U_c is the depth-average velocity, w_s is the settling velocity, a_0 , a_2 , a_3 and b_0 are regression coefficients equal to 0.00076, -0.022 , 0.0079, and 0.243, respectively, and a_1 and a_4 are coefficients for hydrodynamic conditions defined in [7,16].

Although the design concept of dynamic stability enables the optimisation of scour protections, testing conditions of the formula were extended by [18–20], concluding that:

- The design equation does not consider the thickness (t_s) and pile diameter (D_p) variables.
- The limits established for stability showed that some overlapping situations arose; thus, the failure condition could occur for values above the limit of 1.00.
- Like in the static protections, the equation was obtained using only monopile foundations and a short variety of water depths and layer thicknesses.
- The failure criterion used by [7] was the same as in [12]. So, for the reference sub-area of $4D_{n50}^2$, the maximum dynamic behaviour limit of $S_{3D} = 1.0$ has the physical meaning of the scour protection decreasing in thickness by a distance equal to D_{n50} . For scour protections with thicknesses over nD_{n50} ($n > 1$), $S_{3D} = 1.0$ may not be truly representative of failure.
- To quantify the S_{3D} values, the scour protection was divided into fixed sub-areas with an equal area to the monopile cross-section, thus neglecting the damage occurring in the intersection of the sub-areas, the effect of damage in adjacent sub-areas, and not considering the cumulative impact.

An alternative methodology [21] discusses a different way to analyse the damage by creating a mesh of overlapping circles placed in concentric rings, centred at the foundation with an adaptable overlapping distance, angle, and resolution, offering a more detailed assessment of the extent and severity of scour. The concept prevents an excessive lowering of damage due to the averaging of the scour depth over larger sub-areas, reduces deceptive damage interpretations, can be adapted to more complex structures, and enables a much larger population of S_{3D} values quantified over the scour protection's area, thus allowing for the statistical analysis of damage, describing failure with additional parameters (standard deviation, 95th percentile, etc.) rather than only using the maximum damage number. However, this methodology still lacks a detailed definition of the limits to classify

protections as dynamically or statically stable or failures. Hence, the literature shows a need for more physical modelling tests, such as the ones presented here, to address this gap.

The radius of the sub-area (R_{circle}) is given by two parameters, D_{n50} and a multiplication factor (p), Equation (7), which is chosen so that the area of the circle reflects a certain area (A_{sub}), such as, for example, the failure criterion [12]. A percentage of the radius defines the overlapping distance. However, according to [21], the overlapping distance has a reduced influence. No considerable gains were obtained for overlapping distances different from 50%. The S_{3D} is calculated by:

$$S_{3D\text{sub}, \text{circle}} = \frac{V_{\text{circle}}}{D_{n50} \cdot \pi R_{\text{circle}}^2} \quad (6)$$

$$p = 2\sqrt{\frac{n}{\pi}}, \text{ for } A_{\text{sub}} = n \cdot D_{n50}^2 \quad (7)$$

The sub-area arrangement and the mesh characteristics were analysed by [21] by comparing results for different grid ratios. The measurements revealed a strong dependency of the damage number on the size of the sub-area (A_{sub}) and the $S_{3D,\text{max}}$, which increases significantly with increasing grid ratio, thus revealing that the grid ratio selection can completely impact the damage calculation and the scour protection behaviour assessment. This ratio, $\eta_{S3D,\text{grid}}$, is given by:

$$\eta_{S3D,\text{grid}} = \frac{D_{n50}^2}{A_{\text{sub}}} \quad (8)$$

An increase in the grid ratio for the same D_{n50}^2 results in a decrease in the sub-area. Varying the grid ratio also implies a variation in the number of elements. Therefore, a higher value of $\eta_{S3D,\text{grid}}$ indicates that the eroded volume pattern resembles more closely the digital terrain model (DTM). The conclusions derived from the variation of the $\eta_{S3D,\text{grid}}$ highlight the necessity for a uniform and justified selection of a criterion of failure and size of the sub-area. Hence, a statistical analysis was performed by [21] to determine if a specific $\eta_{S3D,\text{grid}}$ led to a convergence of the S_{3D} values, concluding that the variation between $\eta_{S3D,\text{grid}} = 0.25$ ($A_{\text{sub}} = 4D_{n50}^2$) and $\eta_{S3D,\text{grid}} = 0.5$ ($A_{\text{sub}} = 2D_{n50}^2$) seemed to be reasonably small, pointing to the failure criteria suggested by [12] to be a realistic limit to identify failure in scour protections. The research also concludes that, under this methodology, the acceptable damage number for dynamic scour protection needs to be defined, in opposition to the unit value formerly proposed. That implies larger datasets to analyse the influence of the armour layer thickness, the presence of a sand filter layer or geotextile, and the relation with parameters such as the Keulegan–Carpenter (KC) and/or the Reynolds (Re) numbers.

1.3. Deformation and Mobility

More recently, ref. [22] performed an extensive database of 380 tests and claimed that the spatial deformation due to scour around a monopile is not unambiguous and that the classification and interpretation of scour protection's behaviour into classes is not straightforward. It requires the precise definition of what constitutes failure, which can often be “case-specific”. It highlights that calculating the scour deformation depth could be more intuitive for design purposes. It points out that with only two parameters, it can quantitatively describe the deformation of a scour protection and presents a formula to predict it—Equation (9). These two parameters and their interpretable physical meaning are:

- MOB_{top} (relative mobility): measures the hydraulic loading at the top of the scour protection relative to the resistance of the armour layer material. In practical terms, this is the stab parameter presented by [12];
- KC_{tot} (Total Keulegan–Carpenter number): measures and evaluates the contribution of the wave-orbital and steady-current velocities relative to the structure. It measures

the wave stroke asymmetry and the bed shear stress amplification difference around the pile—Equation (10).

$$\frac{S}{D_p} = \left[1 + \frac{3.93}{1 + \exp[-0.74KC_{tot} + 4.75]} \right] \cdot 0.07 \cdot MOB_{top}^{1.65} \quad (9)$$

$$KC_{tot} = \frac{(U_{m,top} + U_c) \cdot T_p}{D_p} \quad (10)$$

where S is the scour depth, $U_{m,top}$ is the wave-orbital velocity at the top of the scour protection, and T_p is the wave peak period.

Equation (9) only considers two parameters to prevent overfitting. Still, the impact of the material grading width, the storm duration, the ratio of water depth vs. pile diameter, the wave–current velocity ratio (U_{cw}), and many others was assessed. However, none seemed to depend on the deformation, such as MOB_{top} and KC_{tot} . Moreover, the results showed a weakly positive correlation between the two parameters, i.e., lower mobility numbers (relatively stable rocks) are associated with lower KC numbers (relatively large piles).

To measure deformations and to recognise the damage areas, a moving-disk filter algorithm was used [23], which separates scour deformation from sinking or sliding. However, the algorithm uses $A_{sub} = 20D_{50}^2$, an area equivalent to a circle with a diameter of $5D_{50}$. It is stated that the sub-area selected by [22] prevents recognition of spot deformation caused by the displacement of larger armour layer material, claiming that the failure criterion suggested by [12] does not eliminate spot deformation. By averaging a local spot deformation within a sub-area of $4D_{n50}^2$ over a circular area of $4D_{50}^2$, it only represents approximately a weight of 20% within the moving average area—the local spot deformation is not neglected but instead weighted differently. Based on the average damage pattern from the 380 tests, it is suggested that according to the respective values of the MOB_{top} and KC_{tot} the scour deformations occur in three distinct areas (upstream side of the pile, deposition area, and downstream side of the pile), which can be correlated to six different deformation pattern classes defined by [23]:

- Class 1: negligible deformation, small settlements, spot deformation, or slight local sinking ($1.5 \lesssim KC_{tot} \lesssim 4$ and $0.20 \lesssim MOB_{top} \lesssim 0.50$).
- Class 2: upstream deformation with negligible downstream deformation, associated with downflow pattern ($1.75 \lesssim KC_{tot} \lesssim 5$ and $0.20 \lesssim MOB_{top} \lesssim 0.85$).
- Class 3: evenly distributed upstream and downstream deformation. Increasing influence of lee–wake vortices ($2 \lesssim KC_{tot} \lesssim 5.5$ and $0.35 \lesssim MOB_{top} \lesssim 0.85$).
- Class 4: mainly downstream deformation. Higher prevalence of lee–wake vortices ($3.5 \lesssim KC_{tot} \lesssim 8$ and $0.40 \lesssim MOB_{top} \lesssim 1.10$).
- Class 5: deep upstream deformation combined with a single deep downstream deformation point. Can be difficult to distinguish from Class 4 but is highly related to the presence of a meaningful steady current ($2.5 \lesssim KC_{tot} \lesssim 9.5$ and $0.35 \lesssim MOB_{top} \lesssim 0.95$).
- Class 6: deformation mainly upstream with a single relatively shallow downstream deformation point. Associated with low current velocities or even only-wave conditions. Horseshoe vortices prevail over lee–wake vortices ($3.5 \lesssim KC_{tot} \lesssim 5$ and $0.6 \lesssim MOB_{top} \lesssim 0.8$);

By comparing tests with similar MOB_{top} and KC_{tot} , but with different contributions from waves and currents (only waves, wave-dominant conditions, and current-dominant conditions), it was observed that the predicted scour depth was in the same order of magnitude of the measured values—Equation (9) had a 0.85 correlation between the measured and the predicted S/D_p values [22]. Nonetheless, the author also underlines that the

formula can sometimes overestimate S/D_p for smaller values of KC_{tot} , and underestimate for larger values of KC_{tot} . Additionally, the deformation and scour pattern observed were significantly different, and sometimes some of the classes were difficult to distinguish, as evidenced by the overlapping range of values for both parameters. This observation was partially attributed to the asymmetry of the orbital wave motion when more intense current velocities exist. It emphasises that combining the hydrodynamic conditions is important to determine where the peak deformation will occur. In contrast, the values of the KC_{tot} and MOB_{top} parameters will predict the possible range of scour depth and damage. Finally, it suggests and emphasises the need to develop a design formula combining scour depth, area, and volume, with guidelines on the volume–area–depth relation and requirements for what constitutes a universal, clear, and unambiguous definition of scour protection failure.

1.4. Hybrid Structures

Although dynamic scour protection systems for monopiles have been the focus of the scientific community, significant knowledge gaps persist, particular due to limited data, and limited experimental studies about structures with complex geometries, hybrid structures, or other marine harvesting technologies in general [8]. The oscillatory or rotational motion of these devices induces additional soil–fluid–structure interactions, potentially causing significant alterations to wave orbital motion, current velocity fields and overall flow patterns. Standard scour protection behaviour and expected scour patterns may no longer apply. Therefore, design guidelines and equations could be misadjusted as they do not consider certain characteristics imposed by these devices. New design equations should consider not only structural and environmental parameters regarding the foundation and the offshore conditions, respectively, but also consider cyclical variations of pressure, disturbance/enhancement of flow patterns, wave reflection/attenuation, impact on soil properties, and vibration increments and/or modifications on the natural frequency of the structure. A review study on cases of scour on WECs and tidal–current energy converters (TECs) only, on WECs used as a protective measure in front of pipelines and monopiles, and even on WECs or TECs incorporated into breakwaters and monopiles, respectively, was performed by [8]. None of those studies used scour protections, and different results were reported: from no scour detection to reductions in the scour rates in the vicinity of structures to detrimental cases where scour rates were enhanced.

Due to the lack of consensus on reports and the absence of scientific studies using scour protections for hybrid offshore foundations, the present work provides a comparative experimental study that applies a riprap scour protection to both a monopile and a hybrid monopile foundation. The hybrid configuration was obtained by an in-house adaptation of a WEC [24–26] to the specific dimensions of the experimental setup. The riprap scour protection was designed based on the configuration and methodology used by [7]. However, instead of determining the varying median stone diameter (D_{n50}) for the intended hydrodynamic conditions, the study estimated the damage number and the scour depth across a range of wave and current combinations for the same scour protection configuration. The approach allowed for predicting the protection's behaviour regime (static, dynamic, or failure), thus enabling a comparison between the expected results and the experimentally measured outcomes. For the scour measurements, the overlapping methodology was used [21] to characterise scour damage in rubble mound scour protections and other marine structures, based on the statistical analysis of damage distribution in flexible meshes of overlapping circular sub-areas. Subsequently, a cautious and meticulous study of all relevant variables was conducted, drawing upon the insights from the literature. The aim was to encapsulate the existing knowledge and most recent research on offshore foundation scour protection, pointing out potential knowledge gaps and research synergies.

The findings reveal that despite the WEC-induced attenuation of the incident hydrodynamic conditions, its oscillatory motion induces complex flow patterns (including enhanced downflow, horseshoe vortices, and lee-wake vortices) that lead to irreversible damage to the riprap protection layer. Moreover, successfully applying the overlapping circles method to determine S_{3D} for scour damage assessment provides a precise damage quantification. However, the obtained damage values raise significant questions regarding the applicability and conservatism of existing design criteria and formulas proposed for monopiles [7,15], and in the context of hybrid foundation systems. This research contributes to a deeper understanding of the hydrodynamic interactions within hybrid offshore energy farms. It provides critical insights for designing and maintaining scour protection measures in such complex environments. These results emphasise the need for new criteria and guidelines for designing protective measures for a broader spectrum of offshore and marine technologies and structures.

2. Experimental Setup

2.1. Wave–Current Flume

The experimental work was carried out in the wave-and-current flume of the Hydraulics Laboratory of the Hydraulics, Water Resources, and Environmental Division (LH-SHRHA) in the Faculty of Engineering of the University of Porto—FEUP (Portugal). The infrastructure is 29 m long, 1 m wide, and 1 m deep, fed by a constant head reservoir. The sediment pit in the middle of the flume has a length of 3.4 m, a width of 1 m, and a depth of 0.4 m. Wave reflections are reduced by a passive wave absorption system [27]. A singular piston-type wavemaker at the upstream side of the flume can reproduce regular, irregular, and solitary waves up to 0.25 m for a maximum water depth of 0.7 m. The experiments were conducted using a geometric scale of 1:50 with incident waves propagating in the direction of the currents [28]. Currents were generated using two intake pipelines with a combined maximum flow capacity of 255 m³/h, ensuring a depth-average mean flow velocity of up to 0.16 m/s for the target water depth $d = 0.4$ m. Tests also include regular/irregular “waves-only” conditions. Irregular waves were reproduced following JONSWAP spectra with a peak enhancement factor (Y) of 3.3, adopting a representation of North Sea conditions for all tests.

For the wave measurements, 4 wave gauges, sampled at 100 Hz, were placed along the flume to measure the water-free surface elevation at selected locations (Figure 1). Two gauges were placed on the seaside near the model to measure the local wave conditions, one on the leeward side to assess the effects of the oscillating surge WEC on the transmission coefficient, and one closer to the wavemaker. The gauge data allow the estimation of the wave-generated bottom orbital velocities (U_m) using a MATLAB (v.R2022b) routine [29], which is necessary to predict S_{3D} accurately. The reflection coefficients were determined for every test, using the incident and reflected wave heights, with values ranging from 0.10 to 0.17.

Current-induced flow velocities were measured through an Acoustic Doppler Velocimeter (ADV)—Vectrino+, Nortek AS, Rud, Norway. The ADV was placed in line with the wave gauges, 2.5 m upstream from the model (Figure 1). The ADV was installed vertically at 0.16 m (0.4d) above the flume ground level, sampled at 100 Hz, with the x-axis pointing in the current direction. Measurements were not made closer to the bed due to the ripple migration and the minimum distance required for a good signal quality of the ADV. Preliminary tests were carried out to adjust the intended U_c values without the influence of waves.



Figure 1. Experimental setup and wave gauge (WG) placement (dimensions in meters).

2.2. Model Layout

A monopile foundation was simulated by acrylic glass with a diameter (D_p) of 110 mm. The pile was positioned around 1 m from the beginning of the sediment box at a 12 m distance from the wavemaker (Figure 1). A circular-shaped dynamic scour protection model was designed [7,16], with a uniform thickness of 2.5 times the nominal median grain size (D_{n50}) and an overall diameter of 5 times the pile diameter (Figure 2). The material yields a $D_{n50} = 3.696$ mm for the armour layer, a density of $\rho_s = 2.66$ mg/m³, and a D_{85}/D_{15} ratio of 3—very wide grading material [30]. Some stones were painted in different colours, creating mainly two concentric rings around the pile (Figure 3). The idea was to have an inner circle demarcating the amplification zone area and to allow a visual observation and distinction of the amount, direction, and displacement of the stones. A polypropylene geotextile with a surface density of 0.330 kg/m² and the same diameter as the armour layer was applied as a filter layer to avoid the washing out of the fine material. As for the sediment box, the sand used had a median diameter of $d_{50} = 0.215$ mm, a density of $\rho_s = 2.59$ mg/m³, and a geometric standard deviation $\sigma_s = \sqrt{(d_{84}/d_{16})} = 1.8$.

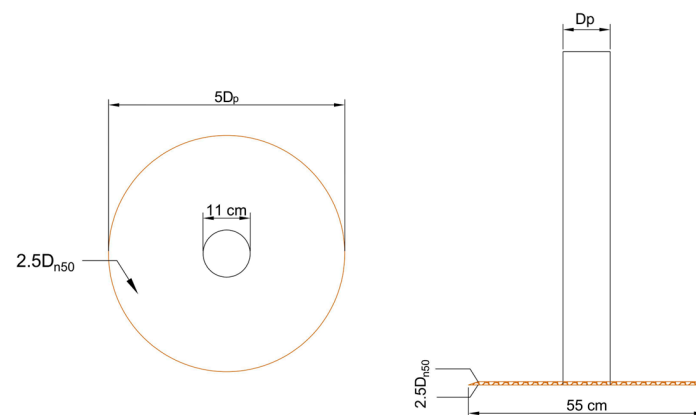


Figure 2. Monopile physical model scheme (Geometric scale: 1:50).



Figure 3. View of the scour protection (with demarcation of the amplification zone).

Regarding the WEC used to perform tests for a hybrid foundation, several devices could be suitable for testing. To assess and analyse the influence of a converter's oscillatory movement, it was decided to adapt and scale down a FOSWEC (floating oscillating surge wave energy converter) device [24–26]. This 6-degrees-of-freedom (DOF) floating WEC was designed, built, and tested at Oregon State University in a geometric scale of 1:33 to develop open-access datasets for validating numerical model codes and create an in-house device suitable for future experimental campaigns regarding marine renewable energy. The device comprises two flaps hinged to a central platform, containing a power take-off (PTO) system and two belt drive systems that operate the flaps. It also has two lateral buoys and openings on the top and bottom of the device (Figure 4).

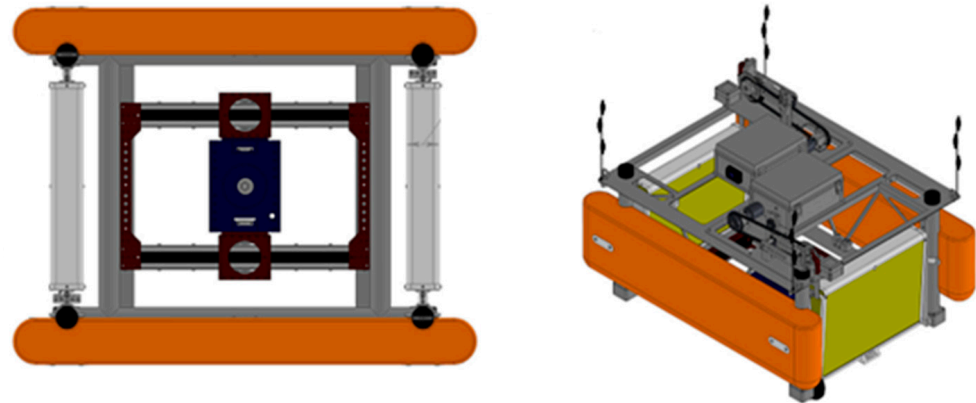


Figure 4. Original FOSWEC scheme [25], adapted and reprinted with permission from © 2020 Elsevier Ltd. (Amsterdam, The Netherlands).

The adapted model built for this study was a simplified version fixed to the monopile 15 cm above the sediment bed through two small cantilever arm braces (Figure 5), locking all the converter's body DOFs. Instead of a PTO system, a simplified system using springs was mounted, with a spring constant that limited the flaps' pitch to a maximum motion angle of $\pm 25^\circ$, Figure 6, the same angle motion of the FOSWEC device [24]. The simplification and substitution of a fully functional PTO system using springs was made, since the primary goal of this study was to assess the impact of the device on the amplification and enhancement of the flow patterns, instead of evaluating the performance and efficiency of the converter's harvesting capacity under the proposed hydrodynamic conditions.



Figure 5. Oscillating surge WEC model construction and installation.

It is recommended to maintain the blockage ratio below the recommended threshold of $1/6$ to minimise wall effects and avoid local acceleration of the flow in the contracted areas or excessive influence of the wall's friction in the hydrodynamics [14]. In the present study, the inherent constraints imposed by both the flume spacing and the necessity to maintain

the structural configurations and dimensions of the OSWEC led to a slight deviation of this ratio, as the device's overall form could not be appropriately scaled without compromising its wave–device interaction or the experimental setup. However, the region for higher blocking is placed at the superficial part of the water depth. Excluding the submerged part of the OSWEC at the monopile foundation, the ratio remained way below $1/6$, i.e., $1/9$. The model was carefully implemented to optimise the balance between achieving a realistic Froude-scaled setup and mitigating the potential blockage effect closer to the seabed to avoid the flow blockage near the protection. Therefore, for the region directly between the OSWEC's base and the sediment bed/scour protection, encompassing a 15 cm vertical distance, the blockage ratio was successfully maintained below the $1/6$ mark. This ensured that the near-bed flow dynamics in this area, which are the most influential on the scour processes, were not influenced by the side wall effects. However, for the model's upper region, the considerations mentioned above and scaling led to a higher blockage ratio. It is acknowledged that this represents a study limitation and may lead to a localised acceleration of the flow and enhancement of streamflow contractions. However, it is essential to contextualise its potential impact on these research objectives. Since the focus was to assess scour damage occurring at the protection due to the oscillating movement of the WEC's paddles, which creates mainly a variation of upward/downward pressure right beneath the device in the scour protection region, enhancing downflow in an area where the blockage criterion was met. Therefore, while the hydrodynamics of the device's upper structure might be subject to some influence, it can be stated that the results regarding the scour damage in the protection remain representative. Future research could benefit from testing in larger-scale facilities to further minimise wall effects across the entire model and validate these findings. Nevertheless, the present study aimed to provide novel and valuable insights into the scour behaviour around hybrid foundations, highlighting critical interactions essential for effective design and understanding scour protections.

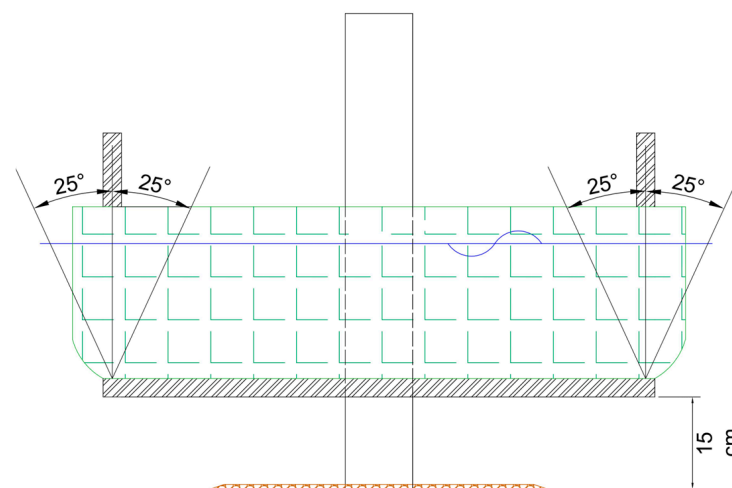


Figure 6. Oscillating surge WEC scheme (Geometric scale: 1:50).

2.3. Hydrodynamic Conditions and Scour Measurement Technique

The hydrodynamic conditions (Table 1) were selected to cover a specific range of wave–current ratios (U_{cw}) and KC numbers while considering other experimental campaigns found in the literature. Tests were run until 3000 waves, except in cases where the failure of the scour protection occurred prematurely. Three types of hydrodynamic conditions used for the monopile (M) and hybrid foundation (MH) were: irregular waves with currents in the same direction (WC), irregular waves only (WI), and regular waves only (WR). For the selected conditions and with the scour protection configuration, Table 2, it was expected to observe different behaviour from the scour protection (static, dynamic, or failure).

Table 1. Physical model hydrodynamic conditions (geometric scale: 1:50).

Test	Number of Waves	d [m]	H _s [m]	T _p [s]	U _m [m/s]	U _c [m/s]	U _{cw}	S _{3D,predicted}	MOB _{top}	KC _{Tot}
M_WC_7	3000	0.4	0.07	1.414	0.080	0.155	0.66	0.08	0.25	3.05
M_WC_11			0.11	1.697	0.143		0.52	0.63	0.41	4.66
M_WC_15.5			0.155	1.980	0.183	0.050	0.21	1.79	0.48	4.28
M_WI_14			0.14	2.263	0.208	-	0.00	3.43	0.53	4.39
M_WR_14			0.14 (Regular)							
MH_WC_7	3000	0.4	0.07	1.414	0.080	0.155	0.66	0.08	0.25	3.05
MH_WC_11			0.11	1.697	0.143		0.52	0.63	0.41	4.66
MH_WC_15.5			0.155	1.980	0.183	0.050	0.21	1.79	0.48	4.28
MH_WI_14			0.14	2.263	0.208	-	0.00	3.43	0.53	4.39
MH_WR_14			0.14 (Regular)							

Table 2. Physical model foundation and scour protection configuration (model values).

Geometric Scale: 1:50	
D _p (m)	0.11
D _{n50} (mm)	3.696
Armour Layer ρ _s (kg/m ³)	2666
Armour Thickness (t _s)	2.5D _{n50}
Armour Extent (D)	5D _p
Filter	Geotextile
D ₈₅ /D ₁₅	3
MOB	0.25–0.53

To measure the seabed bathymetry and the scour of the protection, a FARO® focus laser scanner (2 million points/second, a 3D precision of 2 mm at 10 m, 1 mm standard deviation at 10 and 25 m) was used to obtain high-resolution 3D Digital Terrain Models (DTM). This technique allows the accurate representation of the erodible areas and the respective surroundings; thus, they were taken before and after each experimental test and wave train. The laser scan precision is smaller than the D_{n50} used in the scour protection, hence enabling a high-precision identification of all the armour layer units' movements, even spot deformations. The postprocessing of the DTMs was performed using the Autodesk ReCap and the CloudCompare software (v2.12.4). This resulted in precise point clouds of the seabed, scour protection, and hybrid structure profiles and contours. The DTMs were then used to assess scour depth and the S_{3D,measured} values using a MATLAB routine [21] to employ the overlapping-circle technique. In addition, a visual observation and evaluation, plus a photographic register of all tests, were made to compare the results of the damage number obtained.

3. Experimental Results and Analysis

The experimental test campaign was planned so that the riprap protection and the controlled hydrodynamic conditions were aligned with the study performed by [7] for a more direct comparison of the results and to assess the impact and validation of using the overlapping-circle technique. A discussion of the measured results with the KC_{tot} - MOB_{top} prediction formula [22] was also performed. The results for both formulations differed from the predicted values, opening a meaningful discussion regarding the failure criterion and how scour damage is measured and evaluated.

3.1. Scour Damage (S_{3D})

For all the tests, the overlapping-circle technique was applied by using a $A_{sub} = 4D_{n50}^2$ and an overlapping distance of 50% [21], allowing an objective quantification of the scour protection damage under each test condition. Table 3 summarises all the measured conditions. The U_{cw} values distinguish the three wave-dominated tests ($U_{cw} < 0.44$) from the current-dominated tests ($U_{cw} > 0.44$) [31]. The novel method provided high-resolution representations of the scour patterns and high accuracy of the $S_{3D,measured}$ values and distribution (see Figures in Appendix A). As expected, and generally, S_{3D} correlates highly with the hydrodynamic load intensity. For low-energy conditions, the maximum $S_{3D,measured}$ values were lower and increased with higher wave heights. Also, when comparing the results of the wave-only tests (M_WI vs. M_WR and MH_WI vs. MH_WR), the S_{3D} values were slightly higher when using regular waves, aligned with the findings of a study performed in rubble-mound structures [32], where attributed this difference to the fact that the root mean square (H_{rms}) value for irregular waves tends to be smaller than the wave height for regular waves.

Table 3. Experimental measured conditions for scour protection tests—model values.

Test	Number of Waves	H_s [m]	T_p [s]	U_m [m/s]	U_c [m/s]	U_{cw}	$S_{3D,predicted}$	$S_{3D,measured}$	Visual Classification
M_WC_7_1000	1000	0.072	1.471	0.085	0.157	0.65	0.06	1.43	Slightly Dynamic (all 3000 waves)
M_WC_7_2000	1000	0.073	1.471	0.086	0.157	0.65	0.07	2.11	
M_WC_7_3000	1000	0.073	1.471	0.086	0.157	0.64	0.08	1.95	
M_WC_11_1000	1000	0.100	1.613	0.126	0.156	0.55	0.48	1.73	Dynamic (all 3000 waves)
M_WC_11_2000	1000	0.104	1.613	0.131	0.158	0.55	0.57	1.63	
M_WC_11_3000	1000	0.111	1.613	0.140	0.157	0.53	0.63	1.83	
M_WC_15.5_1000	1000	0.155	2.083	0.223	0.048	0.18	1.79	2.87	Failure
M_WI_14_1000	1000	0.136	2.174	0.199	-	0.00	2.63	2.77	Dynamic (Almost failure, all 3000 waves)
M_WI_14_2000	1000	0.136	2.174	0.199			3.11	3.08	
M_WI_14_3000	1000	0.136	2.174	0.199			3.43	3.08	
M_WR_14_1000	1000	0.142	2.222	0.209	-	0.00	2.63	3.18	Failure (1000 waves)
M_WR_14_2000	1000	0.143	2.174	0.209			3.11	3.30	
M_WR_14_3000	1000	0.143	2.174	0.209			3.43	3.21	
MH_WC_7_1000	1000	0.074	1.299	0.078	0.156	0.67	0.06	1.97	Failure (2000 waves)
MH_WC_7_2000	1000	0.071	1.471	0.084	0.155	0.65	0.07	3.25	
MH_WC_7_3000	1000	0.070	1.471	0.083	0.157	0.65	0.08	2.86	
MH_WC_11_1000	1000	0.110	1.613	0.139	0.157	0.53	0.48	5.38	Failure
MH_WC_15.5_1000	1000	0.156	1.961	0.219	0.051	0.19	1.79	9.81	Failure
MH_WI_14_1000	1000	0.138	2.273	0.205	-	0.00	2.63	7.28	Failure
MH_WR_14_1000	1000	0.137	2.273	0.203	-	0.00	2.63	8.55	Failure

For the monopile tests (M_WC, M_WI, and M_WR), the scour protections exhibited lower damage rates across all the hydrodynamic conditions when compared to their hybrid structure counterparts (MH_WC, MH_WI, and MH_WR), as shown in Figures A1–A20 and Table 3, where very pronounced scour deformations were obtained for similar conditions.

In some cases, nearly double or triple the damage number from the corresponding monopile test was obtained, consistent with the intense sediment erosion, the washout of the armour layer material, and the considerable sinking of the seabed under the filter layer (Figure 7).

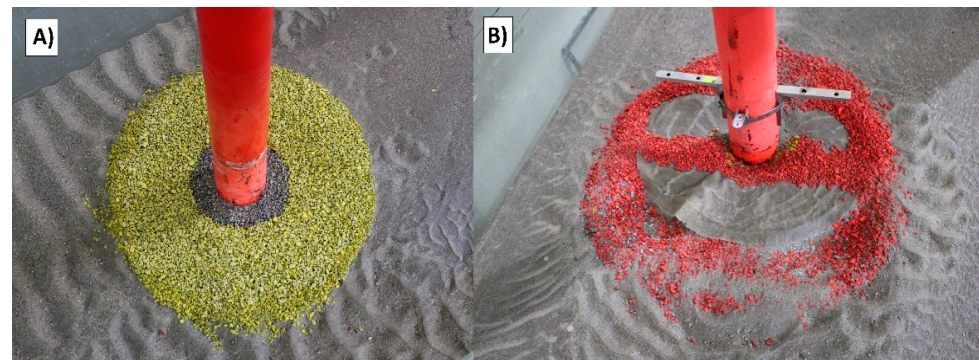


Figure 7. Damage comparison between the tests: (A) M_WR_14_1000 (monopile) and (B) MH_WR_14_1000 (hybrid monopile—test stopped due to large deformation of the armour layer and filter).

For most tests using a hybrid structure, failure occurred within the first 1000 waves. The only hybrid monopile test that provided scour protection support for some of the initial enhanced flow patterns was the MH_WC_7 test, which endured 2000 waves. The flow patterns responsible for the scour mechanism in monopiles are well documented [33]. However, with the results obtained for the hybrid structure, it is reasonable to assume that some of the main mechanisms responsible for scour were definitively enhanced. Due to the oscillatory movement of the paddles, on the front side of the foundation, the downflow was the flow pattern that caused most of the damage. Conversely, in the leeside, the movement of the downstream paddle enhanced the intensity of the lee-wake and counter-rotating vortices. Moreover, due to the dimensions of the WEC, the approaching flow conditions increase the streamline contractions around and beneath the device, which also adds to the overall result.

In contrast, monopiles retained integrity under mild conditions, M_WC_7 and M_WC_11, demonstrating dynamic behaviour unequivocally for the duration of the 3000 waves. For more intense conditions, the protection failed for M_WC_15.5 and M_WR_14 for the first 1000 waves. Although the regular wave-only test failed for the first wave train, the test was continued for comparison with the irregular wave test. The same was done for the hybrid test MH_WC_7, where failure occurred before the 3000-wave limit, but a final wave train was performed for comparison with the non-hybrid counterpart. Regarding the M_WI test, the high S_{3D} value suggested that the scour protection had failed. Still, when visually assessing damage using Figure 8 and comparing it to Figure A10, no distinctive filter exposure was observed despite intense movement of the armour layer units. Therefore, the protection was deemed to be on the edge between the dynamic behaviour and failure.

A noteworthy capacity of dynamic scour protections is to reshape and recover from a specific damage degree due to the allowed movement of the armour layer units [12]. That capacity was empirically observed during the experimental tests, most notably by the tests M_WC_7_2000 to M_WC_7_3000. Furthermore, this characteristic was also manifested in a protection where failure occurred, from MH_WC_7_2000 to MH_WC_7_3000, where a partial recovery from a significant damage rate (quantified as an S_{3D} reduction from 3.25 to 2.86) was observed. While both scenarios exhibit filter exposures, a subset of scour holes identified post-2000-wave train exposure was filled during the 3000-wave train. The backfilling originated from the armour layer units that had previously been displaced (Figure 9)—suggesting a potential for recovery under mild conditions. This observation

raises a pertinent question regarding the potential for scour protections to recover and turn back to dynamic stability after failure.



Figure 8. M_WI_14_3000 test scour protection.

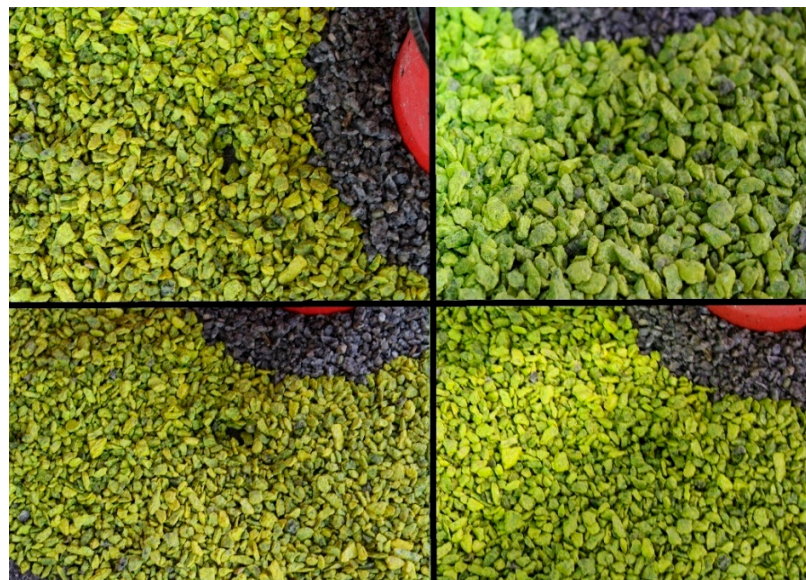


Figure 9. Scour holes (MH_WC_7_2000—left) and refilling (MH_WC_7_3000—right).

A discrepancy is visible when comparing the $S_{3D,measured}$ with those predicted by using Equation (5) formula (Table 3). It can be observed that, in general, the formula underestimates scour for the conditions tested. This is aggravated when dealing with a hybrid structure. The formula underestimates actual damage, suggesting that the formula needs to incorporate other non-linear factors that may occur in more complex or hybrid systems. However, this underestimation also stems from methodological differences in how damage is measured by the approaches developed by [7,21]. As previously mentioned, the methodology established by [7] makes use of fixed sub-areas equivalent to the monopile cross-section, which averages the scour depth over larger areas. Moreover, it does not consider the thickness of the scour protection.

Hence, if the damage number represents the number of protection layers lost to scour as a function of D_{n50} , as indicated by [7], for the model thickness ($t_s = 2.5D_{n50}$), an $S_{3D} = 1.0$ will not be a valid representation that physically failure occurs. Even dynamically stable scour protections were observed by [7,20], for S_{3D} values larger than 1.0, up to 1.25, thus showing that the reference values proposed by [7] can be conservative. On the contrary, the approach developed by [21] allows the use of the criterion of failure suggested by [12], as

the sub-area to be analysed over an overlapping mesh created over the protection. Thus, for a selected A_{sub} , in this case $4D_{n50}^2$, the filter layer exposure and failure should at least occur only when $S_{3D} \times D_{n50} \geq t_s$. Considering this, a comparison of S_{3D} and thickness as a function of D_{n50} could be more informative. Consequently, the failure limit should not be a fixed threshold value independent of the protection thickness, such as $S_{3D} = 1.0$, as proposed by [7], but a range around $S_{3D} = n_s$ for $t_s = n_s \cdot D_{n50}$, accounting for a degree of uncertainty, being that n_s is the number of rock stone size layers [18].

By adopting this perspective, comparing $S_{3D, \text{measured}}$ values to a starting point of $S_{3D, \text{failure}} = 2.5$, determined by the n_s value used during the experimental tests, allows for a clearer visual interpretation of the scour protection's behaviour as a function of the damage number measured using the overlapping method and a more straightforward understanding of the physical meaning of the S_{3D} —see Figures 10–12. The static limit of $S_{3D} = 0.25$ was maintained, as in the research carried out by [7]. It is worth reiterating that for the M_WI test, the values obtained for the damage number, in fact, point to failure for the totality of the 3000 waves, even for $S_{3D, \text{failure}} = 2.5$. This reinforces the idea that the boundary between scour behaviour classification should be defined by a range that accounts for a certain degree of uncertainty instead of a single fixed threshold value.

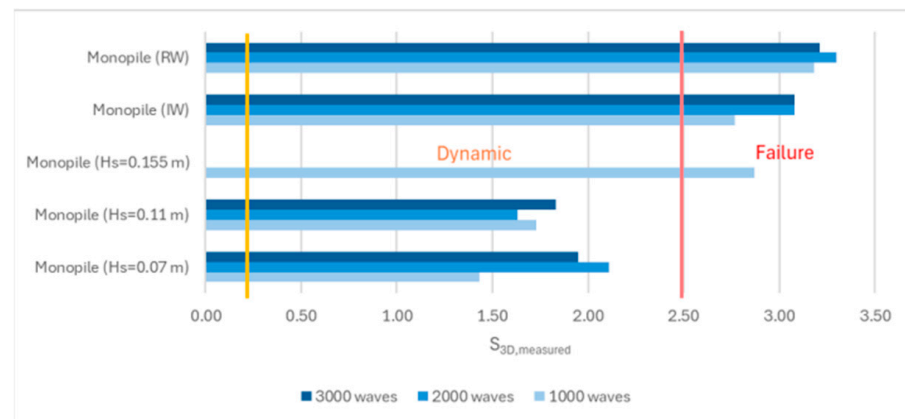


Figure 10. S_{3D} and damage classification for new limits based on the thickness of the scour protection—monopile tests.

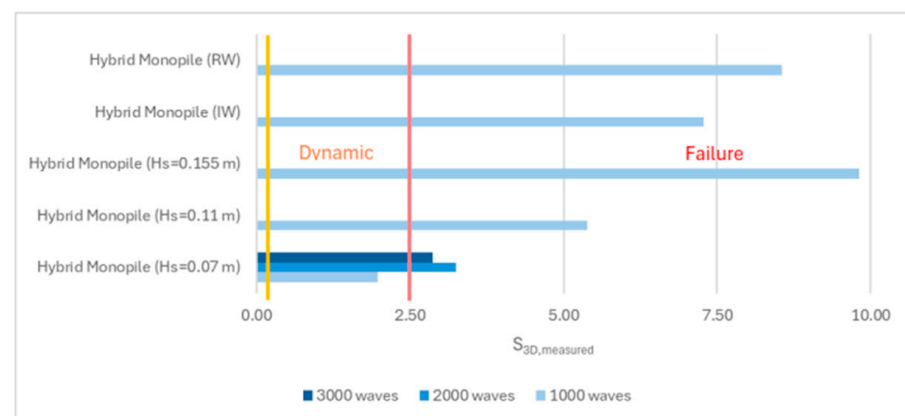


Figure 11. S_{3D} and damage classification for new limits based on the thickness of the scour protection—hybrid monopile tests.

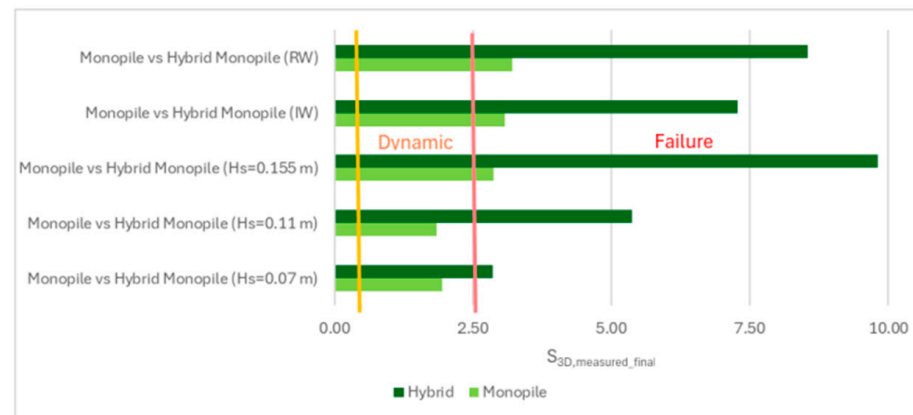


Figure 12. Comparison of S3D values between the monopile and hybrid monopile for the same hydrodynamic conditions.

As a side note, it was detected that in some of the tests (M_WC_7, M_WR, and MH_WC_7), the damage number reached a peak value around 2000 waves and subsequently decreased slightly for 3000 waves or even remained constant in the M_WI test series. This observation highlights that most damage occurs in the first 1000 waves, as observed by [18]. Thereafter, scour holes begin to backfill with surrounding material, after 3000 or even 5000 waves, while other holes may appear, indicating an equilibrium state within this interval.

The development of a design formula combining scour depth, area, and volume, with guidelines on the volume–area–depth relationship, was raised by [22]. A generalisation of the scour volume–area–depth relation, assuming a S_{3D} value for a $A_{sub} = n_s D_{n50}^2$, is given by applying the methodology by [21]:

$$\frac{V_e}{A_{sub}} = S = S_{3D} \times D_{n50} \quad (11)$$

$$\frac{V_e}{S} = A_{sub} = n_s \cdot D_{n50}^2 \quad (12)$$

$$\frac{A_{sub}}{S} = (n_s \cdot D_{n50}) / S_{3D} \quad (13)$$

Moreover, assessing the ratio S/D_p is a widespread practice in the literature when analysing scour rates for unprotected structures. Conversely, determining the deformation for riprap scour protections becomes expendable, since S/D_p becomes reduced, in some cases residual, and does not help the interpretation of the state of the protection. Taking this into consideration and due to the limitations of the fixed sub-areas approach [7], a new ratio was introduced by [18], the damage increase ratio ($\Delta S_{3D}/n_s$), to express the variation of damage between each wave train, while considering the thickness of the scour protection layer by using the number of rock stone sizes. The experimental test results determined a specific range of values of the damage increase ratio for each scour protection behaviour (static, dynamic, failure) for three different durations (0 to 1000 waves, 1000 to 3000 waves, and 3000 to 5000 waves):

- From 0 to 1000 waves: $\Delta S_{3D}/n_s = [0.05–0.09]$ (static), $\Delta S_{3D}/n_s = [0.07–0.39]$ (dynamic), $\Delta S_{3D5000}/n_s = [0.19–0.42]$ (failure).
- From 1000 to 3000 waves: $\Delta S_{3D}/n_s = [0.00–0.03]$ (static), $\Delta S_{3D}/n_s = [0.00–0.12]$ (dynamic), $\Delta S_{3D}/n_s = [0.00–0.50]$ (failure).
- From 3000 to 5000 waves: $\Delta S_{3D}/n_s = [−0.02–0.01]$ (static), $\Delta S_{3D}/n_s = [−0.01–0.07]$ (dynamic), $\Delta S_{3D}/n_s = [−0.04–0.17]$ (failure).

By comparing the values in Table 4, most damage occurs for the first 1000 waves, but at higher rates than the ones proposed by [18]. However, for the 1000 to 3000 wave duration, the values align with the suggested range. By looking strictly for the ratio values, it is possible to determine the speed and rate at which scour damage is developing, but it is hard to determine in which condition and/or behaviour the protection is. Therefore, instead of using the S/D_p and the $\Delta S_{3D}/n_s$ ratio, which do not have a clear physical meaning and can be unclear, and in the case of the $\Delta S_{3D}/n_s$ ratio has overlapping ranges for different behaviours, this study proposes a slight adaptation: S/D_p into S/t_s and $\Delta S_{3D}/n_s$ into S_{3D}/n_s , both for a certain A_{sub} (or $A_{failure}$).

Table 4. Damage increase ratio results $\Delta S_{3D}/n_s$.

Test	Visual Classification	$\Delta S_{3D}/n_s$
M_WC_7_1000	Slightly Dynamic	0.57
M_WC_7_2000		(0–1000 waves) 0.21
M_WC_7_3000		(1000–3000 waves)
M_WC_11_1000	Dynamic	0.69
M_WC_11_2000		(0–1000 waves) 0.04
M_WC_11_3000		(1000–3000 waves)
M_WC_15.5_1000	Failure	1.15
M_WI_14_1000	Dynamic (Almost Failure)	1.11
M_WI_14_2000		(0–1000 waves) 0.12
M_WI_14_3000		(1000–3000 waves)
M_WR_14_1000	Failure	1.27
M_WR_14_2000		(0–1000 waves) 0.01
M_WR_14_3000		(1000–3000 waves)
MH_WC_7_1000	Failure	0.79
MH_WC_7_2000		(0–1000 waves) 0.36
MH_WC_7_3000		(1000–3000 waves)
MH_WC_11_1000	Failure	2.15
MH_WC_15.5_1000	Failure	3.92
MH_WI_14_1000	Failure	2.91
MH_WR_14_1000	Failure	3.42

These slight modifications convert both into more practical, intuitive ratios and are more representative of the scour protection deformation state and the relative amount of armour layer thickness loss. For these ratios, the authors suggest that the limits proposed by [7], 0.25 for static behaviour and 1.0 for failure, could make more sense as a good starting point than for the S_{3D} :

- S_{3D}/n_s or $S/t_s > 1$: failure—filter layer exposed, loss of filter layer and/or seabed lowering;
- $0.25 < S_{3D}/n_s$ or $S/t_s < 1$: dynamic behaviour—loss of thickness in the armour layer and/or movement of the armour layer units;
- $0 < S_{3D}/n_s$ or $S/t_s < 0.25$: static behaviour—no movement, or residual movement, of armour layer units;

- S_{3D}/n_s or $S/t_s < 0$: accretion of sediments around the armour layer unit;

For most tests, a variable limit for the damage number and the S/t_s ratio was used to fit the classification and assessment of the scour protection behaviour for the entire experimental campaign. The protections where failure was detected visually or with the overlapping-circle method correspond to values of $S_{3D} > 2.5$ or $S/t_s > 1.0$ (Table 5, Figures 10, 11 and 13). The same occurs for protections classified as dynamic, where $S_{3D} < 2.5$ or $S/t_s < 1.0$, with the only exception being the M_WI test, for the previously mentioned reasons. Therefore, it is worth mentioning that a failure criterion based on the S_{3D}/n_s or S/t_s is defined by the scour protection properties and geometry and is independent of the foundation used. Possible higher values obtained for hybrid foundations are not an indicator to redefine the failure threshold criterion but an indicator of increased scour damage that eventually should lead to the necessity to upgrade the characteristics of the scour countermeasure. In the end, the overlapping method proved to be valuable in visualising, tracking, and identifying the scour patterns, holes, rate, and consequently the assessment and quantification of the damage and behaviour of each scour protection tested.

Table 5. Scour depth, S_{3D}/n_s , S/t_s , and scour damage comparison.

Test	S [mm]	S/t_s S_{3D}/n_s	S/t_s S_{3D}/n_s (Failure)	$S_{3D,measured}$	$S_{3D,failure}$
M_WC_7_1000	5.29	0.57		1.43	
M_WC_7_2000	7.80	0.84		2.11	
M_WC_7_3000	7.21	0.78		1.95	
M_WC_11_1000	6.39	0.69		1.73	
M_WC_11_2000	6.02	0.65		1.63	
M_WC_11_3000	6.76	0.73		1.83	
M_WC_15.5_1000	10.61	1.15	1.0	2.87	2.5
M_WI_14_1000	10.24	1.11		2.77	
M_WI_14_2000	11.38	1.23		3.08	
M_WI_14_3000	11.38	1.23		3.08	
M_WR_14_1000	11.75	1.27		3.18	
M_WR_14_2000	12.20	1.32		3.30	
M_WR_14_3000	11.86	1.28		3.21	
MH_WC_7_1000	7.28	0.79		1.97	
MH_WC_7_2000	12.01	1.30		3.25	
MH_WC_7_3000	10.57	1.14		2.86	
MH_WC_11_1000	19.88	2.15	1.0	5.38	2.5
MH_WC_15.5_1000	36.26	3.92		9.81	
MH_WI_14_1000	26.91	2.91		7.28	
MH_WR_14_1000	31.60	3.42		8.55	

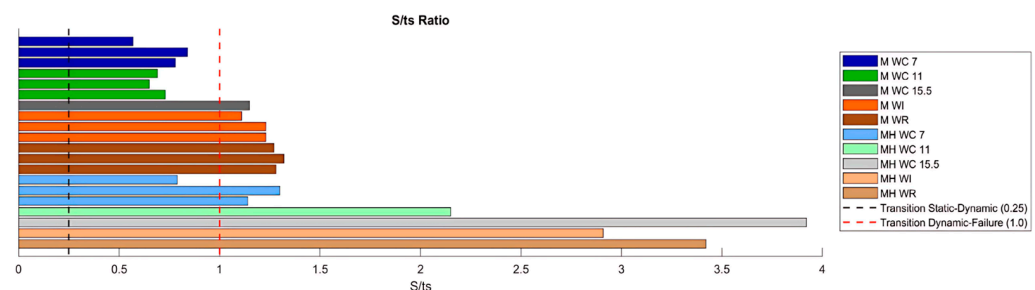


Figure 13. S/t_s ratio values and transition thresholds.

3.2. Overlapping Grid Ratio

It was proven by [21] that the damage number strongly depends on the grid ratio. However, the analysis of the volumetric damage concerning the grid ratio and the convergence between the two variables was made only for two large-scale cases. To expand and compare its dataset with the tests performed during this study, an analysis of the $S_{3D,max}$ results for each test for different $\eta_{S3D,grid}$ was performed. Moreover, since the maximum damage number is valid only for a single value at the deepest point of the scour protection, a statistical study on the development of the standard deviation and the 95% percentile of the S_{3D} was implemented to verify a possible convergence stage.

The grid ratios were selected to cover a variety of A_{sub} values, including the monopile cross section [7], $25D_{n50}^2$ (corresponding to five armour layer units), $4D_{n50}^2$ as in [12], and many others equivalent to the arrangement of multiple or even single armour layer units ($nD_{n50} \times nD_{n50}$) (Figure 14).

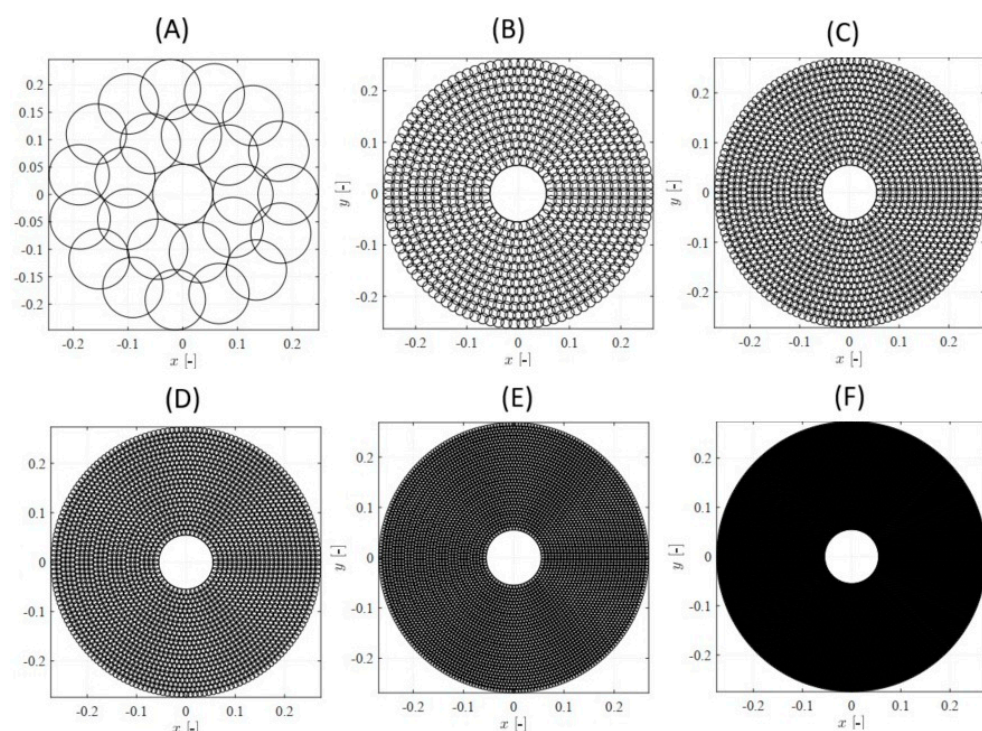


Figure 14. Overlapping-circle arrangement for different $\eta_{S3D,grid}$ and sub-areas: (A) $\eta_{S3D,grid} = 1.43 \times 10^{-3}$, $A_{sub} = A_{pile}$; (B) $\eta_{S3D,grid} = 1/25$, $A_{sub} = 25D_{n50}^2$; (C) $\eta_{S3D,grid} = 1/16$, $A_{sub} = 16D_{n50}^2$; (D) $\eta_{S3D,grid} = 1/9$, $A_{sub} = 9D_{n50}^2$; (E) $\eta_{S3D,grid} = 1/4$, $A_{sub} = 4D_{n50}^2$; (F) $\eta_{S3D,grid} = 1$, $A_{sub} = D_{n50}^2$.

Varying the grid ratio implies a variation in the number of elements, leading to a considerable variation in the maximum value of the damage number. Figure 15 illustrates the case for the M_WC_11_3000 tests. For higher grid ratios, i.e., lower A_{sub} and more sub-areas, the scour pattern becomes closer to the DTM representation. The figure also illustrates the considerable variation of outcomes for different ratios, where for an A_{sub} equal to the cross section of the monopile, the least amount of analysed elements, the maximum damage number detected was negative (accretion of sediments). Conversely, for an A_{sub} equal to a single armour layer unit (D_{n50}^2), S_{3D} was superior to the $S_{3D,failure} = 2.5$ (representative of a meaningless spot deformation in depth).

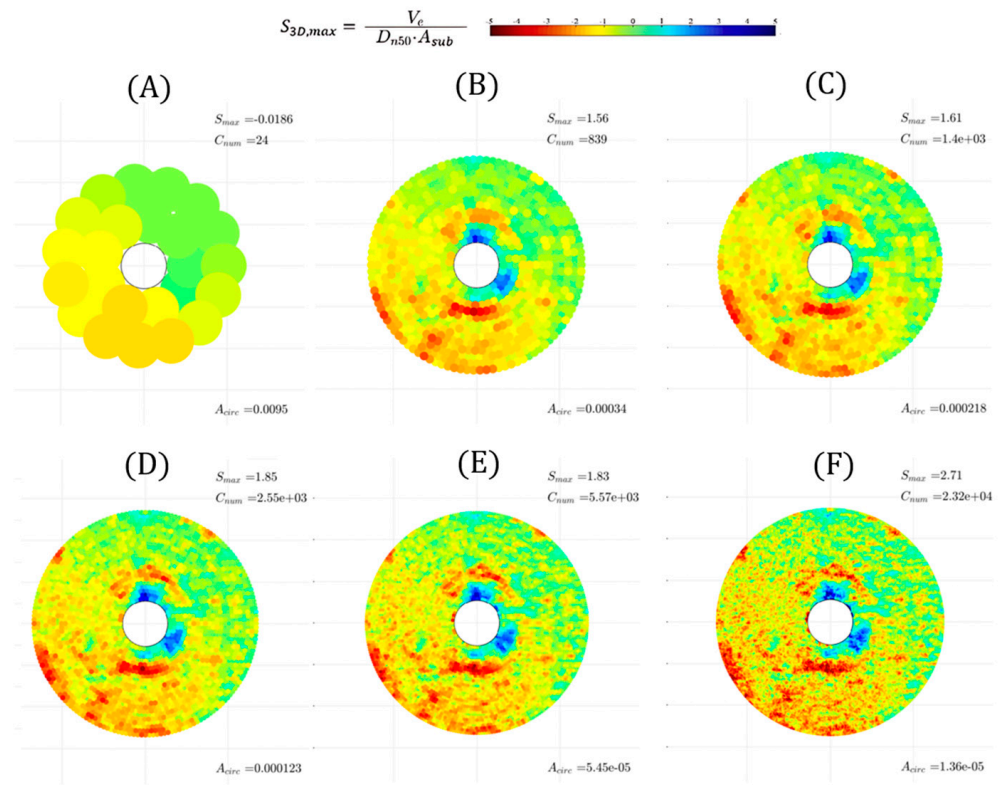


Figure 15. Influence of $\eta_{S3D,grid}$ on $S_{3D,max}$ value for test M_WC_11_3000: (A) $\eta_{S3D,grid} = 1.43 \times 10^{-3}$, $A_{sub} = A_{pile}$; (B) $\eta_{S3D,grid} = 1/25$, $A_{sub} = 25D_{n50}^2$; (C) $\eta_{S3D,grid} = 1/16$, $A_{sub} = 16D_{n50}^2$; (D) $\eta_{S3D,grid} = 1/9$, $A_{sub} = 9D_{n50}^2$; (E) $\eta_{S3D,grid} = 1/4$, $A_{sub} = 4D_{n50}^2$; (F) $\eta_{S3D,grid} = 1$, $A_{sub} = D_{n50}^2$.

The results obtained for the $S_{3D,max}$ vs. $\eta_{S3D,grid}$ for all the tests in the study (Tables A1 and A2) were plotted onto Figure 16 (monopile) and Figure 17 (hybrid monopile). Both plots show similar conclusions as in [21], a very strong dependency and positive correlation of the damage number with the grid ratio and/or size of the sub-area selected, demonstrating that different grid ratios lead to completely different results that would lead to entirely different interpretations of the scour protection behaviour. This is an argument for the necessity of considering a uniform criterion of failure to evaluate the performance of scour protections [21].

By comparing the results and the plots, it is evident that the $S_{3D,max}$ exponentially grows until approximately $\eta_{S3D,grid} = 1/10$ ($A_{sub} = 10D_{n50}^2$). The values seem to stabilise from that grid ratio value until $\eta_{S3D,grid} = 1/4$ ($A_{sub} = 4D_{n50}^2$) and from that point forward starts to increase linearly for cases where the scour damage was quantitatively lower (monopiles), opposite to cases where the damage was significant (hybrid monopile), where the $S_{3D,max}$ value appears to remain almost the same independently from the A_{sub} selected. Nevertheless, from the results obtained, the best range of grid ratios and sub-area to accurately assess the damage number value, for both cases, seems to be situated between $\eta_{S3D,grid} = 1/6$ ($A_{sub} = 6D_{n50}^2$) and $\eta_{S3D,grid} = 1/4$ ($A_{sub} = 4D_{n50}^2$), where residual or almost no differences were observed. These results indicate that the failure criterion $4D_{n50}^2$, Ref. [12] is a reasonable limit to correctly identify failure in a scour protection and an accurate A_{sub} to use on the overlapping method [21].

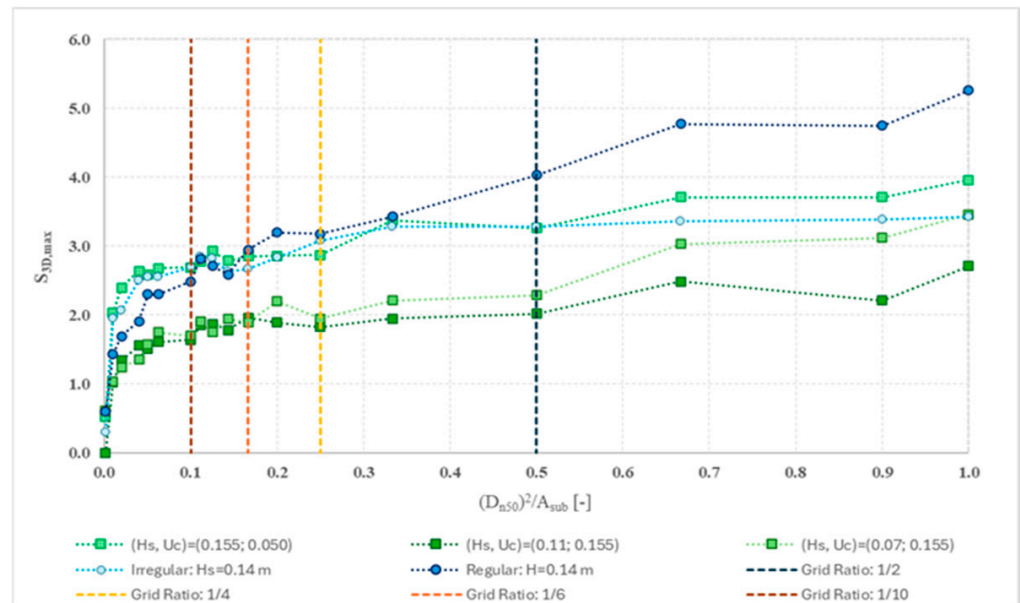


Figure 16. Variation of $S_{3D,max}$ with $\eta_{S3D,grid}$ —monopile tests.

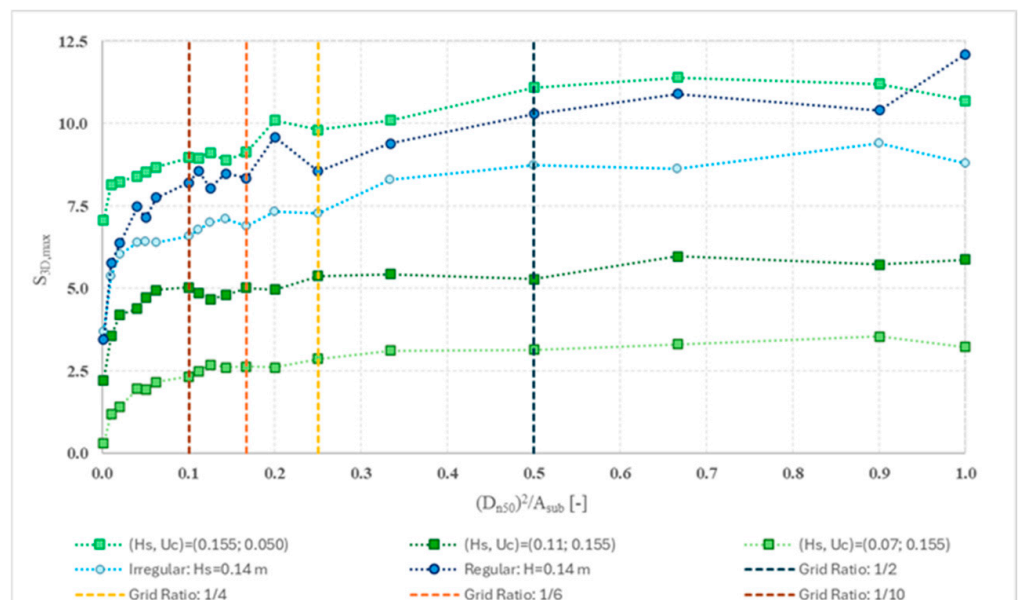


Figure 17. Variation of $S_{3D,max}$ with $\eta_{S3D,grid}$ —hybrid monopile tests.

Since $S_{3D,max}$ seems to be fairly affected by the variation of the grid ratio and affected by minimal changes [21], the standard deviation (Figure 18) and the 95% percentile (Figure 19) of all $S_{3D,sub}$ values for each test were plotted to ensure if the convergence is given for the different grid ratios selected. For both statistical measures, $S_{3D,max}$ vs. $\eta_{S3D,grid}$ for all the tests in the study (Tables A1 and A2) were plotted onto Figure 16 (monopile) and Figure 17 (hybrid monopile). Both plots show similar conclusions as in the study performed by [21], a very strong dependency and positive correlation of the damage number with the grid ratio and /or size of the sub-area selected, demonstrating that different grid ratios lead to completely different results that would lead to entirely different interpretations of the scour protection behaviour. This is an argument for the necessity of considering a uniform criterion of failure to evaluate the performance of scour protections.

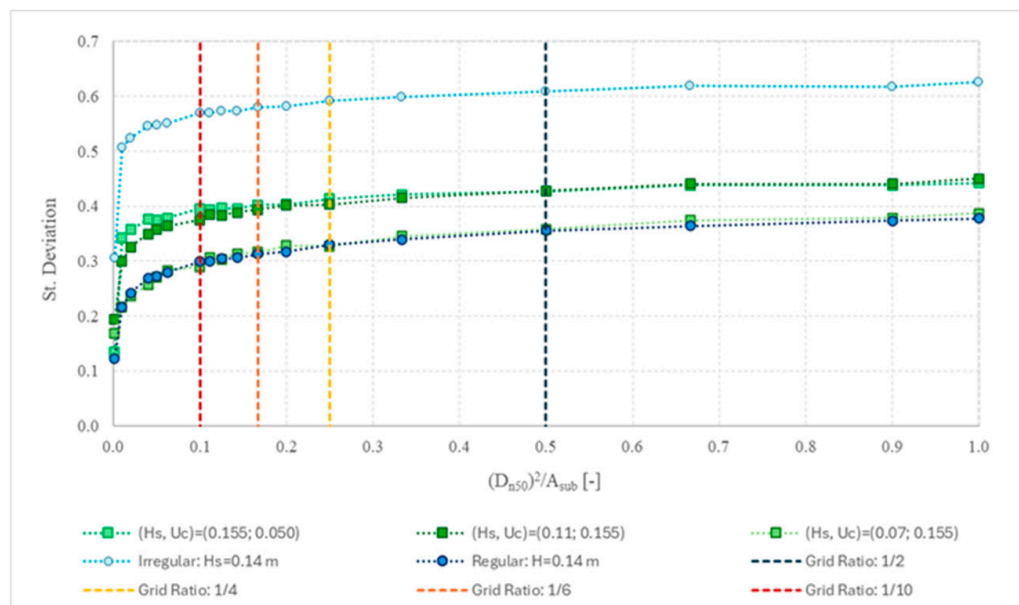


Figure 18. Variation of the standard deviation of $S_{3D,sub}$ with $\eta_{S3D,grid}$ —monopile tests.

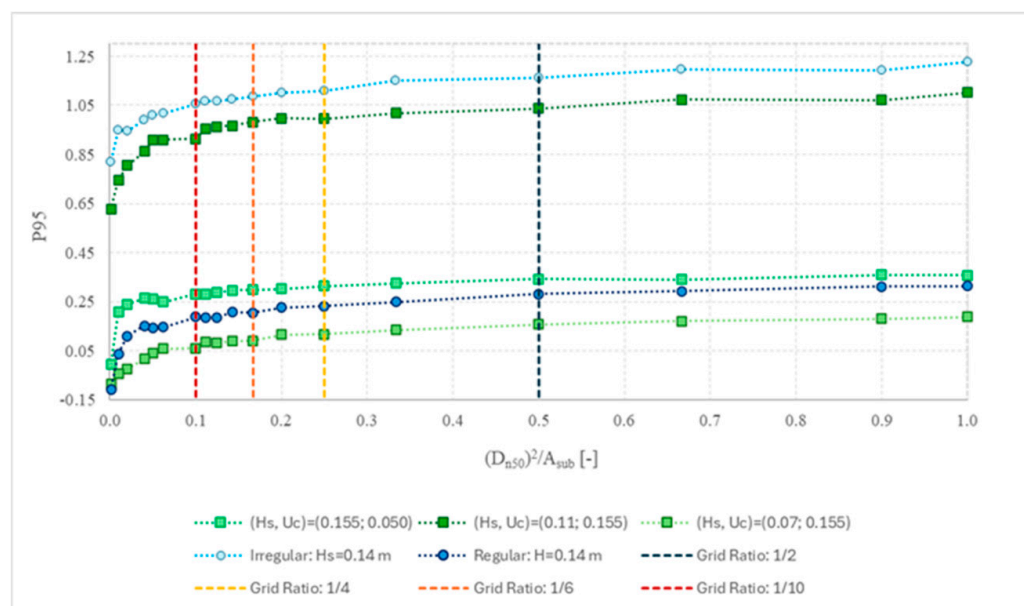


Figure 19. Variation of the 95% percentile (P95) of $S_{3D,sub}$ with $\eta_{S3D,grid}$ —monopile tests.

3.3. KC_{tot} — MOB_{top} Effect and U_{cw} Analysis

In this section, the performance of the scour protection is evaluated using the dimensionless parameters MOB_{top} and KC_{tot} , based on a predictive model developed by [22]. While the proposed formula has proven effective in characterising scour deformation in conventional monopile foundations, its application to hybrid structures was not considered. The MOB_{top} — KC_{tot} framework was considered as having a higher correlation with scour depth and being the best absolute performance evaluator/predictor of a scour protection when compared to the stab parameter or the S_{3D} [22]. However, the calculation of the absolute and dimensionless predicted scour depths (S and S/D_p , respectively) using Equation (9) showed a consistent underestimation for the monopile values measured 2 to 7 times higher than the predicted (Table 6). Similar trends were observed in the hybrid monopile tests, where actual scour depths exceeded the predictions by factors of 7 up to 11.

Table 6. Scour measured vs. predicted values: KC_{tot} — MOB_{top} design formula [22].

Test	Number of Waves	S [mm]	$S_{predicted}$ [mm]	S/D_p	$S_{predicted}/D_p$	KC_{tot}	MOB_{top}
M_WC_7_1000	1000	5.29	1.10	0.048	0.010	3.27	0.26
M_WC_7_2000	1000	7.80	1.10	0.071	0.010	3.29	0.26
M_WC_7_3000	1000	7.21	1.10	0.066	0.010	3.29	0.26
M_WC_11_1000	1000	6.39	2.31	0.058	0.021	4.19	0.36
M_WC_11_2000	1000	6.02	2.64	0.055	0.024	4.29	0.38
M_WC_11_3000	1000	6.76	3.08	0.061	0.028	4.42	0.41
M_WC_15.5_1000	1000	10.61	7.59	0.096	0.069	5.25	0.62
M_WI_14_1000	1000	10.24	3.96	0.093	0.036	4.04	0.51
M_WI_14_2000	1000	11.38	3.96	0.103	0.036	4.04	0.51
M_WI_14_3000	1000	11.38	3.96	0.103	0.036	4.04	0.51
M_WR_14_1000	1000	11.75	4.73	0.107	0.043	4.33	0.54
M_WR_14_2000	1000	12.20	4.73	0.111	0.043	4.24	0.55
M_WR_14_3000	1000	11.86	4.73	0.108	0.043	4.24	0.55
MH_WC_7_1000	1000	7.28	0.99	0.066	0.009	2.79	0.25
MH_WC_7_2000	1000	12.01	1.10	0.109	0.010	3.23	0.25
MH_WC_7_3000	1000	10.57	1.10	0.096	0.010	3.24	0.25
MH_WC_11_1000	1000	19.88	3.08	0.181	0.028	4.40	0.41
MH_WC_15.5_1000	1000	36.26	7.04	0.330	0.064	4.92	0.63
MH_WI_14_1000	1000	26.91	4.40	0.245	0.040	4.35	0.52
MH_WR_14_1000	1000	31.60	4.29	0.287	0.039	4.31	0.51

In a first analysis, these discrepancies may be attributed to the fact that the methodology proposed by [22] relied on a different algorithm [23] to detect deformations and measure scour depths, $A_{sub} = 20D_{50}^2$, that may dilute the localised scour effects when compared to the overlapping-circle method ($A_{sub} = 4D_{n50}^2$). Additionally, the research developed by [22] used larger monopiles— $D_p = 0.15$ to 0.30 m vs. 0.11 m (model values)—different scour protection configurations— $t_s = [1,2] D_{n50}$ vs. $t_s = 2.5D_{n50}$, extent of $3D_p$ vs. $5D_p$, $\rho_s = [2650\text{--}3200]$ kg/m³ vs. $\rho_s = 2666$ kg/m³, and $D_{85}/D_{15} = [1\text{--}3]$ vs. $D_{85}/D_{15} = 3$ —and different model scales. Furthermore, the dataset (20 test points) in this experimental study was sparse when compared to the 380 tests performed by [22].

When a more detailed analysis was carried out, a crucial aspect was identified as a possible contribution to the discrepancy in the prediction values—the gradation width of the armour layer material. As Equation (2) was adopted by [22] to calculate the critical Shields parameter, the protection model in this study is considered a very wide-graded scour protection ($D_{85}/D_{15} = 3$). For this type of scour protection, a lower value of θ_{cr} is recommended by [15] for calculating the stab parameter, which is the same parameter as the MOB [22]. For both foundations, improvements were detected by recalculating the $S_{predicted}/D_p$ with the recommended value $\theta_{cr} = 0.035$ (Table 7 and Figure 20).

For the monopile, despite most values still falling short of accurately predicting the measured results, a substantial improvement was identified— S/D_p values for the M_WC_11, M_WI, and M_WR tests were underpredicted by factors of less than 1.5, while the S/D value for the M_WC_15.5 test was even overpredicted—see Figure 21. Focusing on the results obtained for the hybrid monopiles, the differences between the predicted and the measured S/D_p decreased, but the prediction was still considerably far from the measured scour depths (Table 7, Figures 20 and 21).

The pronounced underprediction values observed for the hybrid foundation (Table 7, Figures 20 and 22), regardless of the θ_{cr} used to determine the MOB_{top} , cannot be solely attributed to the omission of the gradation width in the formula. Rather, it can be reasonably assigned to the presence of the WEC and its major influence on scour. Equation (8) was not developed to capture WEC-induced flow amplifications and associated shear stress

increments generated by the paddles' motion—effects absent from the conditions used to derive the formulation. As the MOB_{top} measures the hydraulic loading relative to the armour layer resistance, its variation depends not only on the stability of the protection but also on changes in the flow patterns. As the KC_{tot} variable measures the contribution of wave-orbital and steady-current velocities relative to the structure, the WEC's paddle motion, by enhancing the flow patterns acting on the foundations, is expected to exert a pronounced effect on both parameters, sufficient to substantially increase the bed shear stress acting on the scour protection to well above the θ_{cr} of the armour layer material. That contribution is not expressed in the formula by means of an amplification or safety factor, leading to a massive underestimation of the predicted scour depth.

Table 7. Comparison of the predicted values using different critical Shields parameters.

Test	Number of Waves	S [mm]	S/D _p	S _{predicted} [mm]	S _{predicted} /D _p	S _{predicted} [mm]	S _{predicted} /D _p
				$\Theta_{cr} = 0.035$		Θ_{cr} —Equation (2)	
M_WC_7_1000	1000	5.29	0.048	1.98	0.018	1.10	0.010
M_WC_7_2000	1000	7.80	0.071	1.98	0.018	1.10	0.010
M_WC_7_3000	1000	7.21	0.066	1.98	0.018	1.10	0.010
M_WC_11_1000	1000	6.39	0.058	4.18	0.038	2.31	0.021
M_WC_11_2000	1000	6.02	0.055	4.73	0.043	2.64	0.024
M_WC_11_3000	1000	6.76	0.061	5.72	0.052	3.08	0.028
M_WC_15.5_1000	1000	10.61	0.096	14.30	0.130	7.59	0.069
M_WI_14_1000	1000	10.24	0.093	7.48	0.068	3.96	0.036
M_WI_14_2000	1000	11.38	0.103	7.48	0.068	3.96	0.036
M_WI_14_3000	1000	11.38	0.103	7.48	0.068	3.96	0.036
M_WR_14_1000	1000	11.75	0.107	9.02	0.082	4.73	0.043
M_WR_14_2000	1000	12.20	0.111	8.80	0.080	4.73	0.043
M_WR_14_3000	1000	11.86	0.108	8.80	0.080	4.73	0.043
MH_WC_7_1000	1000	7.28	0.066	1.87	0.017	0.99	0.009
MH_WC_7_2000	1000	12.01	0.109	1.98	0.018	1.10	0.010
MH_WC_7_3000	1000	10.57	0.096	1.98	0.018	1.10	0.010
MH_WC_11_1000	1000	19.88	0.181	5.72	0.052	3.08	0.028
MH_WC_15.5_1000	1000	36.26	0.330	13.09	0.119	7.04	0.064
MH_WI_14_1000	1000	26.91	0.245	8.47	0.077	4.40	0.040
MH_WR_14_1000	1000	31.60	0.287	7.92	0.072	4.29	0.039

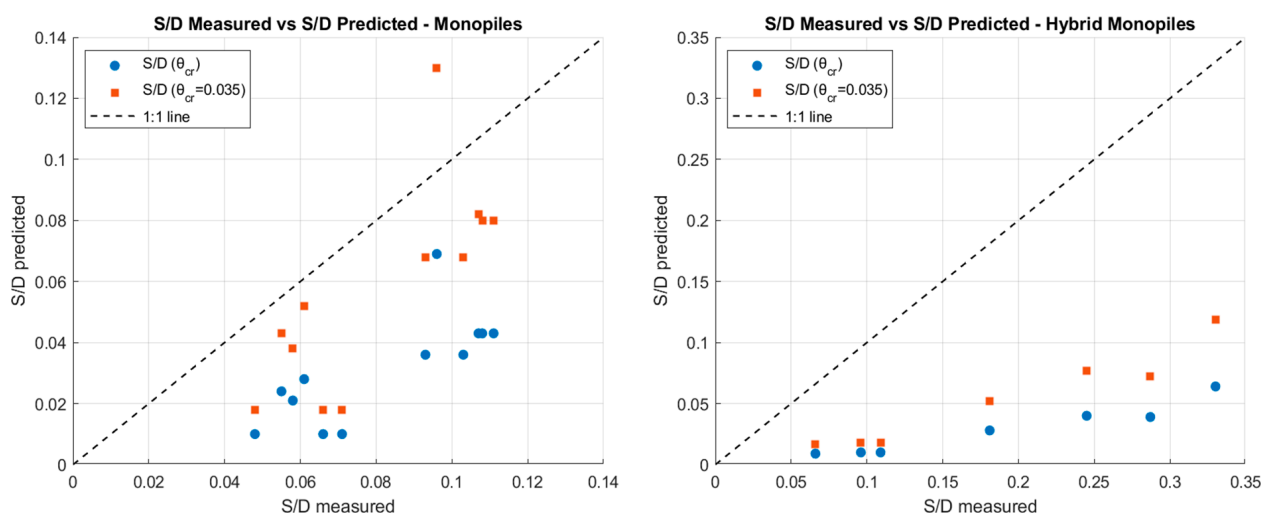


Figure 20. Comparison between measured vs. predicted S/D_p , using different values for θ_{cr} .

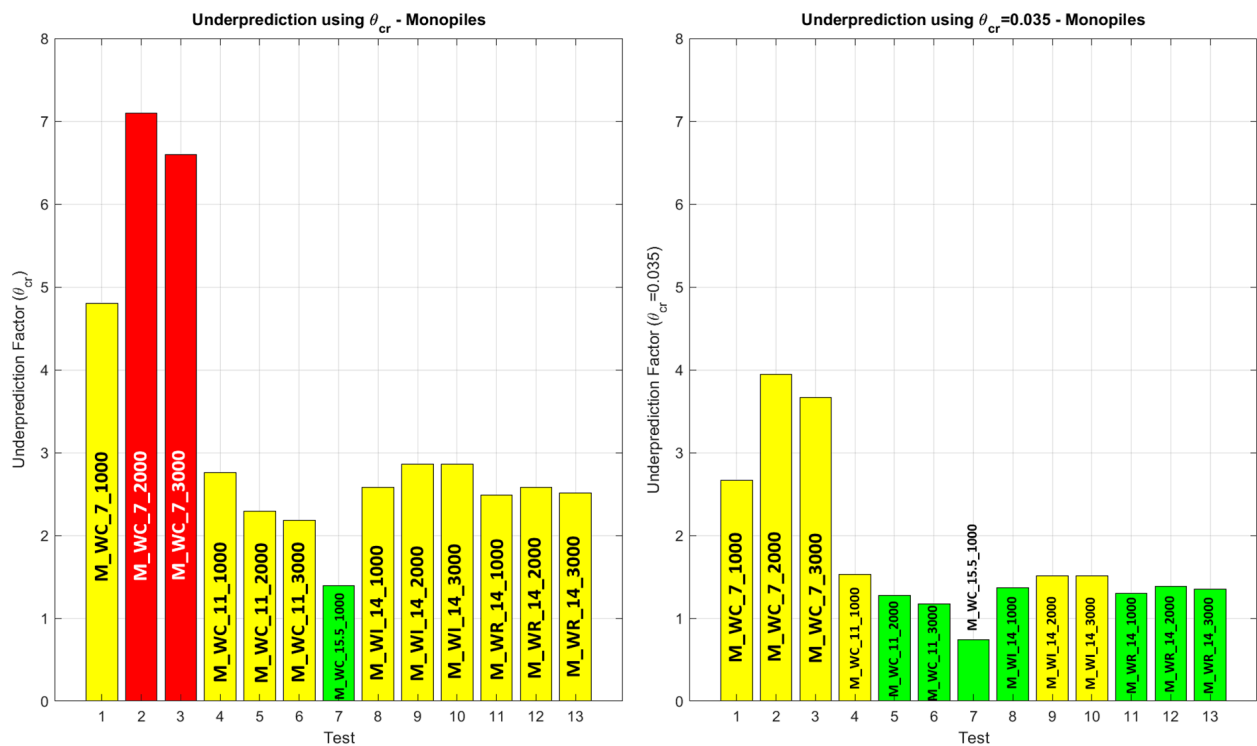


Figure 21. Underprediction factor for monopiles, using different values for the θ_{cr} —green: under 1.5 times; yellow: between 1.5 and 5 times; red: over 5 times.

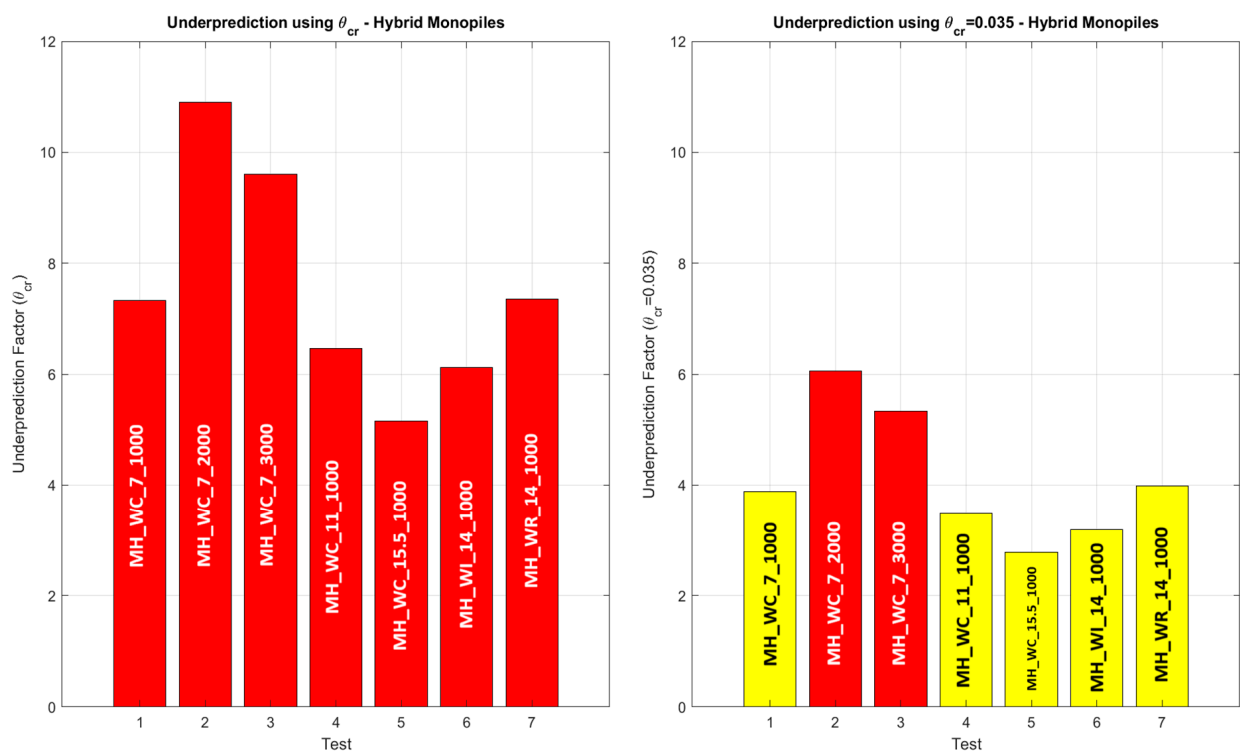


Figure 22. Underprediction factor for hybrid monopiles, using different values for the θ_{cr} —yellow: between 1.5 and 5 times; red: over 5 times.

Nonetheless, the discrepancy between the measured vs. predicted scour depths for the hybrid monopile, in comparison to the monopile foundation, underlines the limitations and insufficiencies that current predictive models have in capturing the complexity that hybrid structures and WEC components and oscillatory movement integration induce

in unsteady flow fields and offshore hydrodynamics. This reinforces the need for new predictive approaches tailored to multifunctional offshore structures that integrate in situ flow and seabed erosion measurements.

With the available metrics for assessing the scour protection condition, the parameter S/t_s (scour depth relative to the protection thickness) or the S_{3D}/n_s (scour damage relative to the number of armour layer rock units) emerges as a more reliable damage indicator and/or predictor than the S/D_p . Unlike the S/D_p ratio, which lacks a clear physical correlation with the specific characteristics of the scour protection's armour layer, such as D_{n50} or overall thickness, both S/t_s and S_{3D}/n_s directly reflect a direct and quantitative measure of the current state of the armour layer. For instance, a specific S/D_p value, even with known protection characteristics, offers limited insight into the protection's behaviour, failing to illustrate whether failure occurred or if the scour countermeasure is in a dynamic/static state. While it quantitatively distinguishes different erosion magnitudes, it provides only a generalised appreciation of damage without offering significant qualitative information regarding the protection status or comparable information regarding the protection's integrity. It provides greater utility in contexts where scour is measured without a scour protection, where the magnitude of the seabed erosion relative to the monopile offers a generalised sense of risk of ultimate and/or serviceability limit-state to the foundation. Conversely, S/t_s and S_{3D}/n_s directly and unambiguously translate the percentage of protection in the evaluated area that has been eroded, offering a clear and actionable understanding of its condition. Furthermore, for hybrid foundations, where enhanced flow patterns due to the paddles' movements and increased turbulence affect the erosion of the rubble-mound material, these parameters also offer sufficient credibility and a simpler visual representation and interpretation of the protection's behaviour.

Although the classification of scour protections into deformation classes with the evaluation of MOB_{top} - KC_{tot} is considered by [22] to be more useful than the standard behaviour classification (static, dynamic, and failure), it also acknowledges that the evaluation is not so straightforward and sometimes hard to determine. As shown in Figures 23 and 24, most of the tests fall within the range of several deformation classes. An attempt to assess a specific deformation class for each test was made considering the description provided by [22] and the photographic record made during the tests, plus the DTMs and S_{3D} distribution results in Figures A1–A20—see Table 8.

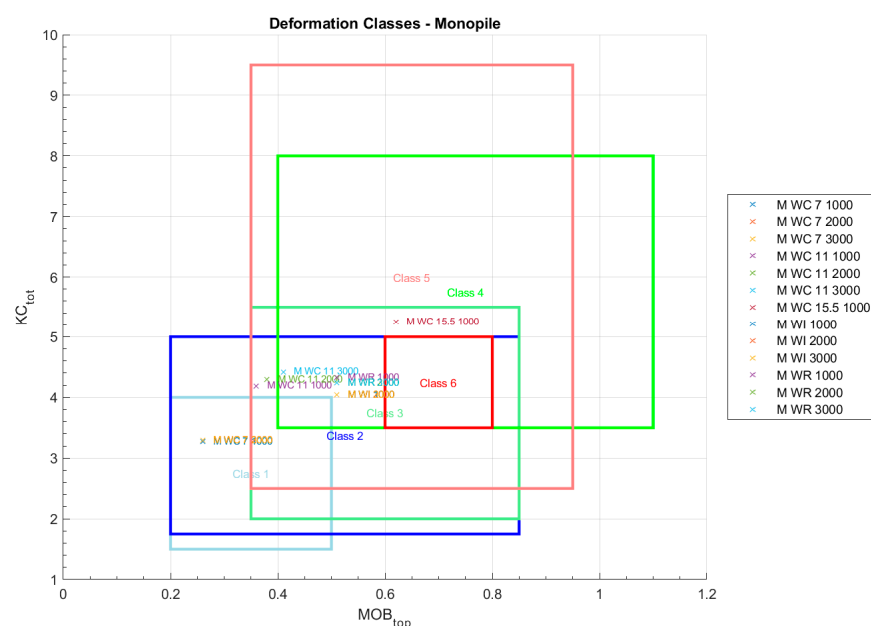


Figure 23. Deformation classes for monopile tests.

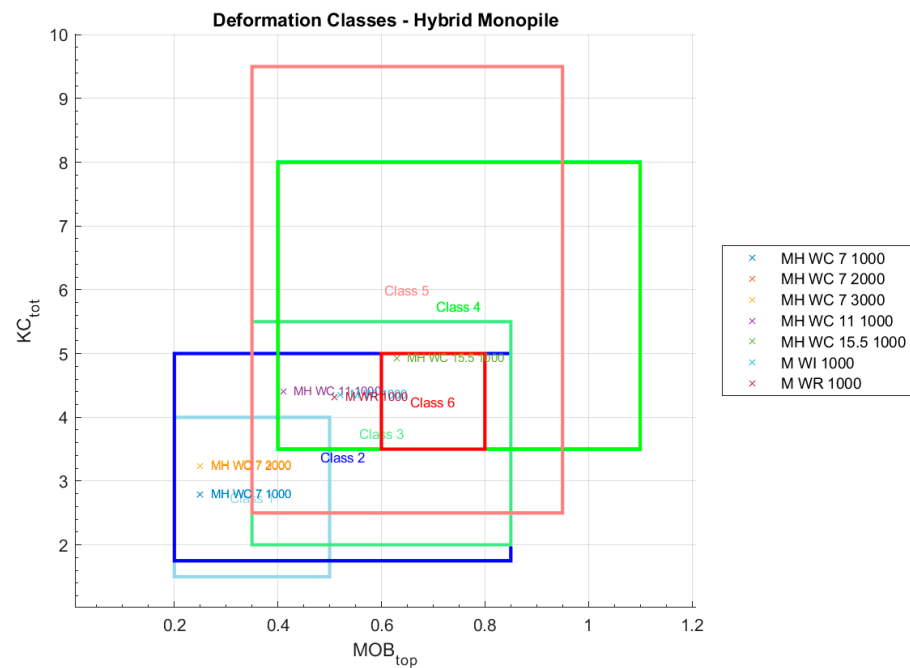


Figure 24. Deformation classes for hybrid monopile tests.

Table 8. Assessment of deformation class according to the criteria defined in [22].

Test #	Deformation Class Assessment	Possible Classes (Figures 23 and 24)
M_WC_7_1000	Class 1	Class 1 or 2
M_WC_7_2000	Class 1	
M_WC_7_3000	Class 1	
M_WC_11_1000	Class 1	Class 2, 3, or 5
M_WC_11_2000	Class 1	Class 2, 3, or 5
M_WC_11_3000	Class 3	Class 2–5
M_WC_15.5_1000	Class 2 (or 6)	Classes 3–5
M_WI_14_1000	Class 2 (or 6)	Classes 2–5
M_WI_14_2000	Class 2 (or 6)	
M_WI_14_3000	Class 2 (or 6)	
M_WR_14_1000	Class 2 (or 6)	Classes 2–5
M_WR_14_2000	Class 2 (or 6)	
M_WR_14_3000	Class 2 (or 6)	
MH_WC_7_1000	Class 1	Class 1 or 2
MH_WC_7_2000	Class 3	
MH_WC_7_3000	Class 3	
MH_WC_11_1000	Class 4+	Class 2–5
MH_WC_15.5_1000	Class 3+	Classes 2–6
MH_WI_14_1000	Class 6+	Classes 2–5
MH_WR_14_1000	Class 6+	Classes 2–5

Although the monopile tests were found to fall within one of the expected classes of deformation, a distinction was made in [22] based on whether the deformation occurred predominantly in the upstream or downstream area of the pile. When analysing the experimental tests in this study, it was observed that the damage occurred mainly within the vicinity of the pile, way inside the amplification area, mainly on the right and left sides.

Moreover, in some cases, the deformation pattern was not evident in the photographic registration. It was only perceptible using the DTMs and the S_{3D} results using the overlapping technique described in [21]. Additionally, according to the description of each class made by [22], the M_WC_15.5, M_WI, and M_WR tests should fall in class 6, since that class is associated with tests using low current velocities or cases with wave-only conditions. The tests M_WC_11_1000 and M_WC_11_2000 were classified as being in class 1, despite Figure 23 showing them outside of that class boundary. However, it was also reported in [22] that many tests expected to fall within a certain class may lie within the limits of other classes, or even outside of all defined class boundaries, due to significant overlaps.

Regarding the hybrid monopile tests, only the MH_WC_7 test sequence was in identifiable conditions to be placed within one of the described classes. For all the remaining tests, the scour damage was too excessive to identify a possible dominant location for the deformation in the protection or lack thereof. Therefore, considering the definition of each class presented in [22], each test was classified into the most appropriate class, considering the hydrodynamic conditions used in each test, and by adding a “+” sign in front of it, as a note of the extensive damage rates observed.

While categorising deformations by classes is deemed by [22] as a more useful classification, the fact is that it is not a linear, practical, or trivial task. From low to extreme scour deformations, distinguishing and classifying them could be challenging due to overlapping or even superposition of classes. Furthermore, it is possible to have deformation classes outside any boundary condition. This makes this classification system a highly subjective tool and less intuitive than the standard classification (static, dynamic, failure). However, directly comparing the MOB_{top} and KC_{tot} to the damage number proved noteworthy.

Overall, S_{3D} tends to increase with higher values of both variables (Figure 25), and regarding the monopile tests, it has a higher correlation with MOB_{top} number than the KC_{tot} parameter (weak correlation). Since MOB_{top} measures the hydraulic loading relative to the resistance of the armour layer, essentially reflecting the potential for erosion/movement of the armour layer units, it provides high-quality information about the scour protection resistance to the loads and whether it might fail. Therefore, it directly captures the actual effects of the main scour mechanisms on scour, resulting in a higher correlation with the damage number. On the other hand, despite KC_{tot} being a measure of the wave-current contribution relative to the structure, which is directly related to the shear stress amplification and vortex shedding around the monopile, primary causes of scour, in the end, it is a composite metric. Consequently, it may obscure the direct contribution of each hydrodynamic component to scour under varying flow conditions, as they may vary independently. Given that multiple wave-current regime combinations may yield identical KC_{tot} values, relying on this parameter may result in less accurate interpretations regarding the primary scour driver. This could explain the observed low correlation with the damage number.

As for the hybrid monopile tests, since severe scour deformations were observed, a high correlation between both KC_{tot} and MOB_{top} to S_{3D} was expected. The interaction between the WEC paddles and the flow leads to a highly energetic near-bed environment. The resulting scour deformation is influenced by intensified oscillatory flow patterns (captured by KC number) and increased hydraulic stress acting on the seabed protection (captured by MOB parameter). As a result, the high correlation with damage number was confirmed, indicating that scour is governed jointly by enhanced shear stresses and the armour layer’s ability, or lack thereof, to resist them.

As the relation between the S_{3D} and the MOB_{top} - KC_{tot} model showed mixed results across the different structures, a more in-depth analysis was conducted. The analysis considers the influence of KC_{tot} (wave-current contribution), the KC number (wave contri-

bution), and the KC_c (current contribution). Additionally, an evaluation of the U_{cw} ratio in relation to the S_{3D} was also performed, since prior studies [31,34–38] have reported a general trend of increased scour depths for higher U_{cw} values under varying conditions. It is reported in the literature that for the same U_{cw} value, scour depths tend to increase for higher KC numbers [34]. That observation was considerably more pronounced in wave-dominant regimes. As U_{cw} increases, that correlation starts to weaken, and for $U_{cw} > 0.65$, scour depths remained almost constant and independent of KC number.

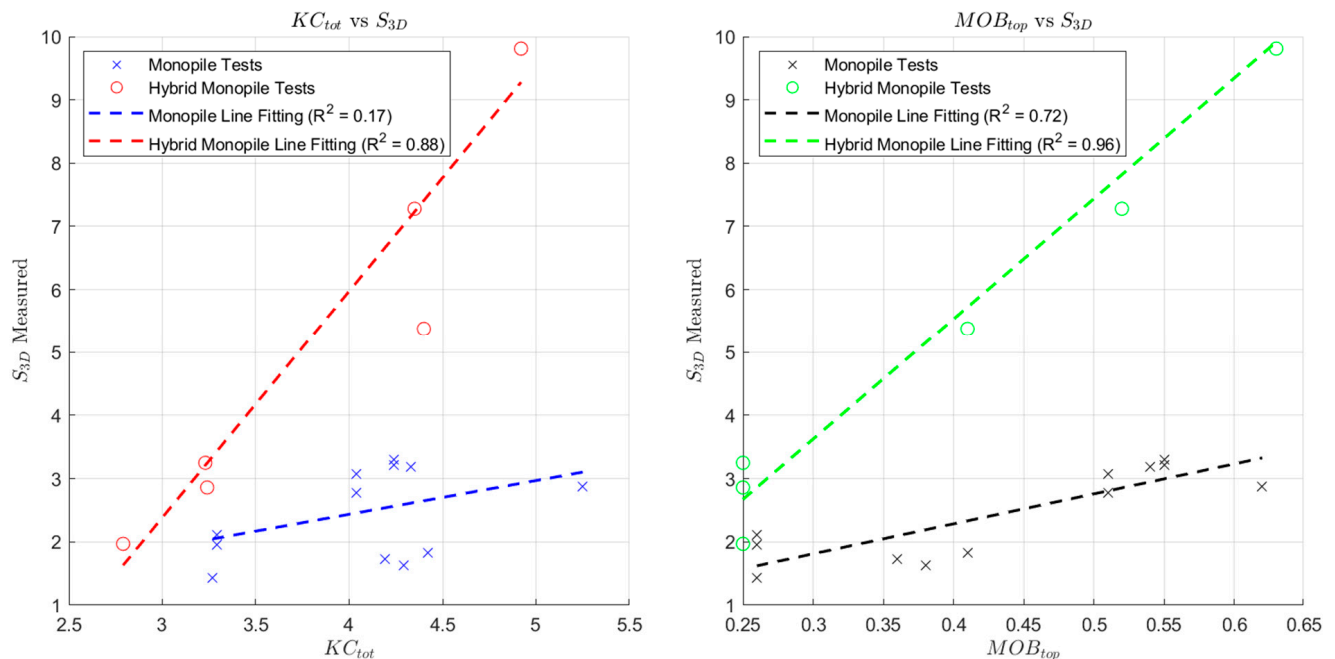


Figure 25. Damage number comparison with KC number (left) and MOB parameter (right).

As previously mentioned, although the KC_{tot} is directly associated with shear stress amplifications and scour, a clearer notion of the main scour drivers for each foundation emerges when its wave (KC) and current (KC_c) components are considered separately (Table 9). For the hybrid monopile, the results exhibit strong positive correlations between the KC_{tot} and KC , underscoring the predominant influence of wave-induced velocities enhanced by the WEC on the scour development (Figure 26). The moderate inverse correlation with the KC_c , Figure 27, indicates a comparatively lower influence of currents on scour for this type of structure. Conversely, for the monopiles, a strong positive correlation with the KC and a strong negative correlation with KC_c were identified—Figures 26 and 27. This observation supports the earlier assertion that the combined parameter may mask the distinct influences of each individual hydrodynamic component to scour, since for the same KC_{tot} value, multiple KC and KC_c combinations are possible. In the end, the strong correlation of damage with KC and KC_c , despite the weaker correlation observed with the KC_{tot} , is an indicator that monopile scour is highly dependent on the complex interaction between the two main hydrodynamic loads, which may not be fully encapsulated by a single combined parameter.

When interpreting the specific influence of the four parameters (KC_{tot} , KC , KC_c , and U_{cw}) on the damage number, any assessment should be made carefully. The apparent inverse correlation between the U_{cw} and S_{3D} (Figure 27) reflects the hydrodynamic conditions selected for the tests, in which higher S_{3D} values occurred for lower U_{cw} ratios as well as higher wave heights with lower current velocities (high KC and low KC_c). In contrast, lower scour damage rates were recorded for tests with higher U_{cw} ratios, which corresponded to lower wave heights and higher current velocities (low KC and high KC_c).

However, when analysing tests with comparable KC_{tot} values, e.g., M_WC_11 ($U_{cw} = 0.55$, $KC_{tot} \approx 4.2$ to 4.4 , $KC \approx 1.9$ to 2.1) vs. M_WR_14 ($U_{cw} = 0$, $KC_{tot} = KC \approx 4.2$ to 4.3), the test with the higher KC number (M_WR_14) presented almost a 60 to 90% increment on the S_{3D} value. Furthermore, when comparing the wave-only tests (M_WI vs. M_WR), both with the same U_{cw} value, the test series with a higher KC number presented slightly higher scour damage, as reported by [34]. As for the tests with higher U_{cw} ratios, the ones with smaller KC numbers presented similar S_{3D} values for the monopile tests, slightly higher for the $H_s = 0.07$ m and $U_{cw} = 0.65$ combination versus the $H_s = 0.11$ m and $U_{cw} = 0.55$ one—consistent with the observations reported by [31,34–38].

Table 9. $S_{3D,measured}$, U_{cw} , KC , KC_c , and KC_{tot} comparison.

Test	U_{cw}	KC	KC_c	KC_{Tot}	$S_{3D,measured}$
M_WC_7_1000	0.65	1.17	2.10	3.27	1.43
M_WC_7_2000	0.65	1.19	2.10	3.29	2.11
M_WC_7_3000	0.64	1.19	2.10	3.29	1.95
M_WC_11_1000	0.55	1.90	2.29	4.19	1.73
M_WC_11_2000	0.55	1.98	2.31	4.29	1.63
M_WC_11_3000	0.53	2.12	2.30	4.42	1.83
M_WC_15.5_1000	0.18	4.34	0.91	5.25	2.87
M_WI_14_1000		4.04	0.00	4.04	2.77
M_WI_14_2000	0.00	4.04	0.00	4.04	3.08
M_WI_14_3000		4.04	0.00	4.04	3.08
M_WR_14_1000		4.33	0.00	4.33	3.18
M_WR_14_2000	0.00	4.24	0.00	4.24	3.30
M_WR_14_3000		4.24	0.00	4.24	3.21
MH_WC_7_1000	0.67	0.95	1.84	2.79	1.97
MH_WC_7_2000	0.65	1.15	2.08	3.23	3.25
MH_WC_7_3000	0.65	1.14	2.10	3.24	2.86
MH_WC_11_1000	0.53	2.10	2.30	4.40	5.38
MH_WC_15.5_1000	0.19	4.01	0.91	4.92	9.81
MH_WI_14_1000	0.00	4.35	0.00	4.35	7.28
MH_WR_14_1000	0.00	4.31	0.00	4.31	8.55

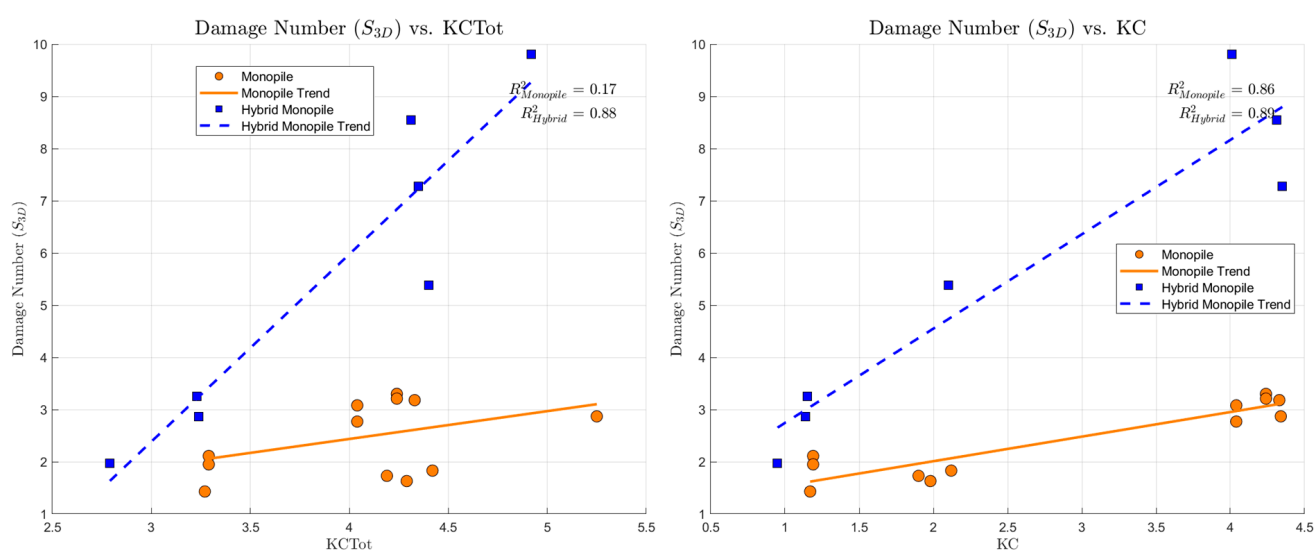


Figure 26. S_{3D} analysis for the KC_{tot} and KC number.

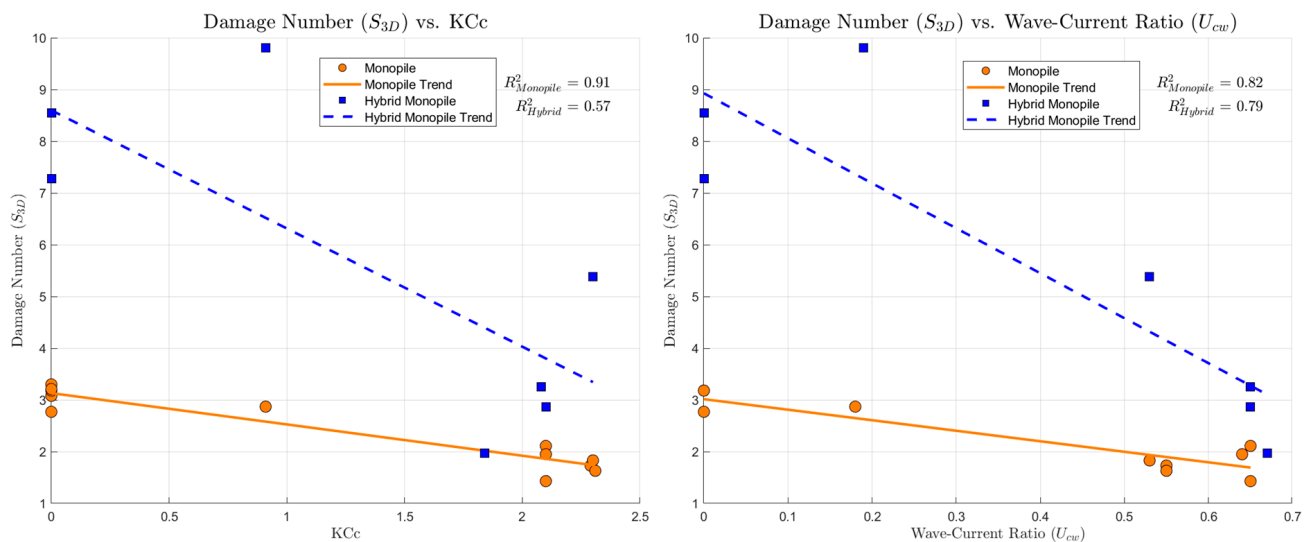


Figure 27. S_{3D} Analysis for the K_{Cc} and the U_{cw} ratio.

Overall, the results point to the fact that scour damage increases with increasing K_C values, regardless of the prevailing regime.

When comparing the monopile test results with the hybrid monopile, it is evident that the influence previously observed for lower U_{cw} ratios was more pronounced for the hybrid monopile tests. That difference can be attributed to the unique hydrodynamic interactions generated by the oscillating paddle movement of the OSWEC. In wave-dominated regimes, that oscillatory motion induces substantial variations in the local flow velocities and conditions. These interactions enhance bed shear stresses, turbulence, and flow accelerations around the structure, acting as a supplementary source of scour-inducing force, thus promoting increased sediment transport when compared to conventional monopile foundations under similar conditions.

3.4. Wave Transmission (C_{Tr}) and Wave Reduction (C_{Red}) Coefficients

The main goal of the experimental campaign was to assess damage to the scour protection of two different types of foundations. However, converting a standard monopile into a hybrid structure by incorporating a WEC revealed significant flow patterns and hydrodynamic differences. Since the focus was not on the performance of the WEC, the captured energy efficiency or the power per unit front was not calculated. Instead, straightforward metrics such as the wave transmission coefficient (C_{Tr}), which compares the seaside wave height to the leeside wave height in each test, and the wave reduction coefficient (C_{Red}), which compares the wave heights between a monopile test and a hybrid monopile test for the same hydrodynamic condition, highlight how both foundations, including the device, influence wave attenuation.

For monopile-only tests, the C_{Tr} consistently remains near 100% (Table 10), indicating minimal interference with the incoming wave. The structure's narrow cross-section contributes to this behaviour, allowing waves to propagate with negligible attenuation, reaffirming the limited wave sheltering capacity—deviations in the coefficient do not exceed $\pm 5\%$. In contrast, for hybrid monopiles, the integrated WEC allows a significant reduction in the C_{Tr} , especially for higher wave heights, where almost 25% of wave reduction on the leeside was observed. These results were achieved using a simplified mechanical system to actuate the WEC paddles, suggesting that a fully functional PTO system could achieve even greater attenuation. The results support the premise that hybridisation effectively increases the dissipative capacity, enhancing wave absorption and reducing transmitted wave energy. On the other hand, as a negative impact, it increases the flow contraction and

the wave–current velocities (not quantified in this study) between the WEC’s bottom and the scour protection.

Table 10. Wave transmission coefficients (C_{Tr}).

Test	Number of Waves	C_{Tr} (%)
M_WC_7_1000	1000	100.0
M_WC_7_2000	1000	100.0
M_WC_7_3000	1000	100.0
M_WC_11_1000	1000	105.0
M_WC_11_2000	1000	104.8
M_WC_11_3000	1000	102.7
M_WC_15.5_1000	1000	98.7
M_WI_14_1000	1000	99.3
M_WI_14_2000	1000	97.8
M_WI_14_3000	1000	96.3
M_WR_14_1000	1000	101.4
M_WR_14_2000	1000	102.1
M_WR_14_3000	1000	100.0
MH_WC_7_1000	1000	94.6
MH_WC_7_2000	1000	94.4
MH_WC_7_3000	1000	94.3
MH_WC_11_1000	1000	81.8
MH_WC_15.5_1000	1000	76.8
MH_WI_14_1000	1000	75.4
MH_WR_14_1000	1000	86.1

While some seaside C_{Red} values (Table 11) for the hybrid monopile show slight negative values, i.e., wave enhancement up to 9%, this was attributed to the intense scour that eroded out the protection and caused the lowering of the seabed, which increased the water depth, creating conditions for bigger waves to be registered without breaking. The leeside C_{Red} values (Table 11) consistently reflect the substantial wave height reduction across all the hybrid tests, up to almost 30%. These results highlight the potential of WECs as promising components for integration into offshore structures. They may serve not only as a booster for renewable energy and power generation but also as a protective element that shields offshore structures and mitigates the effects of severe coastal erosion [8,9]. Nevertheless, the optimisation and strategic integration of PTO systems appear critical for addressing the scour enhancement associated with such devices. This phenomenon could otherwise undermine the overall efficiency of the hybrid structure.

Table 11. Wave reduction coefficients (C_{Red}).

Test	Number of Waves	Seaside C_{Red} (%)	Seaside C_{Red} (%)
M_WC_7 vs. MH_WC_7	1000	−2.7	2.9
	1000	2.8	9.0
	1000	4.3	10.6
M_WC_11 vs. MH_WC_11	1000	−9.1	16.7
M_WC_15.5 vs. MH_WC_15.5	1000	−0.6	27.5
M_WI_14 vs. MH_WI_14	1000	−1.4	29.8
M_WR_14 vs. MH_WR_14	1000	3.6	22.0

Despite the presence of the WEC, a reduction in transmitted wave height was observed compared to the incident wave. However, the scour damage to the protection was concurrently enhanced. This suggests that the rotational angle of the converter's paddle and its distance to the seabed must be considered a critical design criterion to mitigate excessive scour or damage in the protection. When using an OSWEC as a protective measure for a pipeline, it was concluded by [39] that scour was reduced by increasing the angle between the flap and the seabed, which translated to a reduction in the flap's rotation relative to its vertical axis, thereby minimising its oscillatory movement and velocity.

Regarding the distance of a converter to the seabed, the influence of the tip clearance (defined as the vertical distance between a rotating blade and a stationary point) for tidal-current energy turbines was investigated by [40,41], with [40] specifically studying turbines attached to a monopile. Both studies demonstrated that scour was increased by the converter due to enhanced local velocities, downflow, and the occurrence of horseshoe vortices. A 10–20% increase in scour extent and a 30% increase in the scour depth were reported by [41]. Furthermore, it was observed that scour increased faster with lower distances to the bed profile. Nonetheless, it was also concluded that equilibrium scour is independent of tip clearance—a continuous decrease in the distance to the sediment bed, after a certain point, did not translate to a significant increase in the scour depth [41].

While this study maintained a fixed tip clearance, based on operational recommendations for the WEC, it is important to highlight that this parameter significantly influences scour development and could be critical to the future of hybrid foundations. Upcoming studies should consider a range of tip clearance distances and their interaction with other variables associated with the WEC and foundation geometry to quantify their impact under various hydrodynamic conditions. This would allow for a more comprehensive understanding of its influence on scour and ultimately support the development of tailored design criteria for scour protection of hybrid foundations incorporating WEC devices.

4. Conclusions

Experimental results revealed that, despite the WECS's ability to attenuate incident hydrodynamic conditions, reducing leeward wave heights up to almost 30%, the oscillatory motion of the convergent paddles induced complex flow patterns. These patterns, which include downflow, horseshoe vortices, and lee-wake vortices, intensified scour mechanisms and led to severe scour on the armour layer unit, including the erosion and lowering of the seabed near the structure.

Applying the overlapping-circle methodology [21] to determine S_{3D} number proved effective and precise in quantifying the damage rate, allowing for a detailed characterisation of its distribution. The analysis of the influence of the grid ratio ($\eta_{S3D,grid}$) on the quantification of $S_{3D,max}$ showed a strong dependency of this parameter on the selected circle sub-area size (A_{sub}), reinforcing the need for a uniform failure criterion. The results suggest that a grid ratio between 1/6 and 1/4, corresponding to sub-areas of $6D_{n50}^2$ and $4D_{n50}^2$, may be suitable for evaluating the damage number, validating, to some extent, the failure criterion suggested by [12] as a reasonable limit. However, the measured damage values raise significant questions about the applicability and conservatism of existing design criteria and formula [7].

The comparison between the monopile and hybrid monopile tests demonstrated a clear difference in the scour rate and the damage number (S_{3D}). Riprap protections on hybrid foundations suffered significantly higher damage, resulting in pronounced deformations and, in many cases, premature failure (often within the first 1000 waves), unlike monopiles, which, under mild conditions, maintained integrity or exhibited dynamic behaviour. Although some protection configurations showed some capacity for reshaping

and recovery, even after significant damage, in the case of the hybrid monopile, the intensity of the flow patterns induced by the WEC led to irreversible damage to the armour layer. These findings suggest that existing design criteria, particularly those developed for monopiles [7], are insufficient to comply with more complex and hybrid configurations. It can be argued that evaluating the S/t_s or S_{3D}/n_s ratio emerges as a more reliable and representative damage indicator for riprap scour protections than the S/D_p ratio or $S_{3D} > 1.0$ failure limit suggested by [7]. The proposed limits for S/t_s or S_{3D}/n_s align better with the experimentally observed behaviour of the scour protections.

The scour prediction formula developed by [22], which relies on MOB_{top} and KC_{tot} parameters, was found to consistently underestimate the scour deformation observed during the tests, mainly for the hybrid foundation ones. This discrepancy may be related to this study's small dataset, differences in model scales, or even differences in the sub-areas of each measurement methodology. Hence, the methodology proposed by [22] also proved unsuitable for accommodating the increased complexity introduced by a WEC in a hybrid foundation system. However, a strong correlation was established between S_{3D} and KC_{tot} number, as naturally, the scour damage has a higher relation to the shear stress amplification and vortex shedding around the monopile. Moreover, although [22] reported no clear dependency on some parameters, such as gradation width, thickness, and extent, future studies could benefit from assessing the contribution of some of these parameters as they could exert a measurable influence on scour under combined wave–current and WEC-induced loading. Ideally, bridging the S_{3D} with the MOB_{top} - KC_{tot} model could be extremely valuable for developing a more robust approach to damage prediction for both monopiles and hybrid foundations.

This research also contributes to a deeper understanding of hydrodynamic interactions in hybrid offshore foundations, underlining the need to revise existing scour protection design frameworks. While based on a small dataset, the results point towards new design criteria, with guidelines that should incorporate structural complexities and dynamic load interactions to account for a broader spectrum of offshore and marine harvesting technologies, recognising the complexity introduced by hybrid structures and WEC motion.

In summary, the novel contributions and main takeaways are hereby highlighted:

- **Application of a scour protection in a hybrid monopile-WEC system:** comparative assessment of scour damage with a monopile foundation.
 - **Paddle-based WECs can intensify scour in hybrid foundations:** although the used OSWEC device attenuated incoming wave heights by almost 30%, its oscillatory movement generates complex flow patterns and significantly increases the scour damage.
- **Application and evaluation of the innovative overlapping-circle 3D method:** demonstration of its effectiveness and high-resolution scour quantification capabilities of the method proposed by [21], while comparing it with two other different methods [7,22], making a sensitivity analysis to understand the need for a methodological standardisation.
 - **Overlapping method revealed limitations in existing design damage analysis methods:** the overlapping method effectively quantified scour damage via S_{3D} number, providing more insights into its behaviour, completing the information acquired from the studies performed by [7,22], mainly for hybrid configurations. However, its high sensitivity to the grid ratio indicates that the optimal value should fall within the 1/4 and 1/6 ratio interval, which aligns with the proposal made by [21].

- **Identification of limitations in existing design standards and predictive formulas:** the results lead to questioning the conservatism of existing design standards and their inability to capture WEC-induced enhanced flow complexities.
 - **Hybrid monopile riprap protections exhibited early failure:** when compared to standard monopile tests, the scour countermeasures applied to hybrid structures showed markedly higher damage rates, often failing within the initial 1000 waves, thus indicating that the current design methods do not accommodate the dynamic loads induced by WECs.
- **Proposal of alternative performance-aligned scour metrics:** S/t_s and/or S_{3D}/n_s ratios offer more accurate and straightforward indicators for quantifying and evaluating riprap scour protection performance in complex offshore environments by shifting the comparative/relative referential from the foundation to the protection itself.
 - **Alternative S/t_s and S_{3D}/n_s indicators shown to be reliable:** these two relative scour damage ratios better represent the actual riprap state and performance under hydrodynamic loading than the traditional S/D_p or $S_{3D} > 1.0$ threshold, offering a more reliable basis for future design approaches.
- **Framework for advancing design methodologies in hybrid offshore foundations:** to update predictive tools that account for dynamic structural effects and vortex-induced shear amplifications of coupling (extra) devices, to promote safer, more adaptable infrastructures for marine harvesting technologies.

Future research should prioritise expanding the experimental test matrix to include a broader range of hydrodynamic scenarios, alternative scour protection configurations, and different WEC devices. It also should address secondary erosion behind riprap protections since it may become significant under long-term operational conditions. While the present study focused on the performance of scour protection under a maximum of 3000 waves, aligned with most tests reported in the literature and consistent with the duration used to develop the current design criteria, it represents a step toward understanding the short- to mid-term behaviour of such protective systems. Subsequent studies should aim to complement this research through extended physical/numerical modelling campaigns (e.g., over 5000 waves) and field observations to assess potential long-term damage mechanisms, including secondary erosion. Moreover, the recoverability capacity, an indicator of dynamic stability, registered during the tests should also be evaluated for long-term durations as well, to determine whether the backfilling reflects a sustainable resilience or merely a temporary delay of failure. Comparative tests using different types of filter layers would be valuable to observe if the phenomenon persists across different configurations or if it may be a signal of progressive failure. Such efforts would help validate whether existing design standards sufficiently tackle these longer-term effects.

The use of a simplified spring-based mechanism over a PTO in the present research allowed for a controlled assessment of the first-order influence of WEC paddle motion on scour. To more accurately determine the direct influence of the converter, future tests should incorporate a fully operational PTO system to consider the damping effects, as it is expected to significantly affect the flap dynamics, alter the flow patterns, and ultimately influence the scour damage around the foundation. Furthermore, a direct quantification of the local flow enhancement induced by the hybrid structure should be assessed via a CFD model. Such a model would enable the determination of the influence of the converter's paddle motion on the resulting pressure field variations, quantify the enhancement in the bed shear stress acting on the armour layer, and delineate the relative contribution of each flow pattern to the scour damage measured on the scour protection.

Addressing these knowledge gaps will enable the expansion of the existing datasets and raise the current understanding of the key physical mechanisms driving scour in WECs and hybrid systems. This is essential for advancing the comprehension of scour damage processes and ultimately to develop a robust predictive framework. Such efforts are critical to improve or propose new design methodologies and formulations that would be capable of accurately capturing the complex interactions in these intricate marine and offshore environments.

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Abbreviations

The following abbreviations are used in this manuscript:

ADV	Acoustic Doppler Velocimeter
A_{failure}	Area of failure
A_{sub}	Area of the overlapping-circle sub-areas
a_0, a_2, a_3	Regression fitting coefficients
a_1, a_4	Coefficient for hydrodynamic conditions
b_0	Regression fitting coefficient
C_{Red}	Wave reduction coefficient
C_{Tr}	Wave transmission coefficient
D	Scour protection's armour layer extent
D^*	Dimensionless grain size
D_{cr}	Critical stone size
D_p	Pile diameter
D_{n50}	Nominal stone diameter of the scour protection
D_{15}	15th percentile of scour protection material grading
D_{50}	Mean stone diameter of the scour protection material
$D_{67.5}$	67.5th percentile of scour protection material grading
D_{85}	85th percentile of scour protection material grading
DTM	Digital Terrain Model
D	Water depth
d_{16}	16th percentile of sediments
d_{50}	Mean diameter of sediments
d_{84}	84th percentile of sediments
F_r	Froude number
FOSWEC	Floating Oscillating Surge Wave Energy Converter
GBF	Gravity-based Foundation

g	Gravitational acceleration
H	Wave height
H_{m0}	Spectral significant wave height
H_s	Significant wave height
KC	Keulegan–Carpenter number (wave contribution)
KC_c	Keulegan–Carpenter number (current contribution)
KC_{tot}	Total Keulegan–Carpenter number (wave–current contribution)
MOB	Mobility parameter
MOB_{top}	Mobility parameter on the top layer of scour protection
N	Number of waves
n_s	Number of rock stone sizes (layers)
$OSWEC$	Oscillating Surge Wave Energy Converter
OWT	Offshore Wind Turbine
p	Multiplication factor for overlapping-circle sub-area
R_{circle}	Radius of overlapping-circle sub-area
Re	Reynolds number
S	Scour depth
$S_{predicted}$	Predicted scour depth
S/D_p	Relative scour depth
S/t_s	Scour depth relative to the scour protection thickness
$S_{predicted}/D_p$	Predicted relative scour depth
S_{3D}	Damage number
$S_{3D,failure}$	Damage number for failure limit
$S_{3D,max}$	Damage number (maximum)
$S_{3D,measured}$	Damage number (measured)
$S_{3D,predicted}$	Damage number (predicted)
$S_{3Dsub,circle}$	Damage number for overlapping-circle sub-area
S_{3D}/n_s	Damage number relative to the number of rock stone sizes (layers)
s	Specific density (ρ_s/ρ_w)
$stab$	Stability parameter
T	Wave period
T^*	Dimensionless time scale
T_m	Mean wave period
$T_{m-1,0}$	Energy wave period
T_p	Wave peak period
TEC	Tidal-current Energy Converter
t_s	Scour protection thickness
U_c	Depth-averaged current velocity
U_{cr}	Mean threshold velocity of sediments
U_{cw}	Wave–current velocity ratio
U_m	Wave orbital bottom velocity
$U_{m,top}$	Wave orbital bottom velocity at the top of the armour layer
$V_{A,max}$	Maximum erosion volume
V_{circle}	Volume of overlapping-circle sub-area
V_e	Eroded volume
WEC	Wave Energy Converter
w_s	Settling velocity
α	Amplification factor
$\Delta S_{3D}/n_s$	Damage increase ratio
$\eta_{S3D,grid}$	Grid ratio
θ	Shields parameter
θ_{cr}	Critical Shields parameter
θ_{max}	Maximum dimensionless wave–current-induced shear stress

ν	Kinematic viscosity of water
ρ_s	Density of rock material
ρ_w	Water mass density
σ_s	Standard deviation of sediments
τ_{cr}	Critical bed shear stress
τ_m	Mean combined bed shear stress (current and wave-induced)
τ_{max}	Maximum combined bed shear stress (current and wave-induced)
Y	Wave spectrum peak enhancement factor

Appendix A

Monopile and Hybrid Foundation S_{3D} Results: Overlapping Technique Results ($A_{sub} = 4D_{n50}^2$)

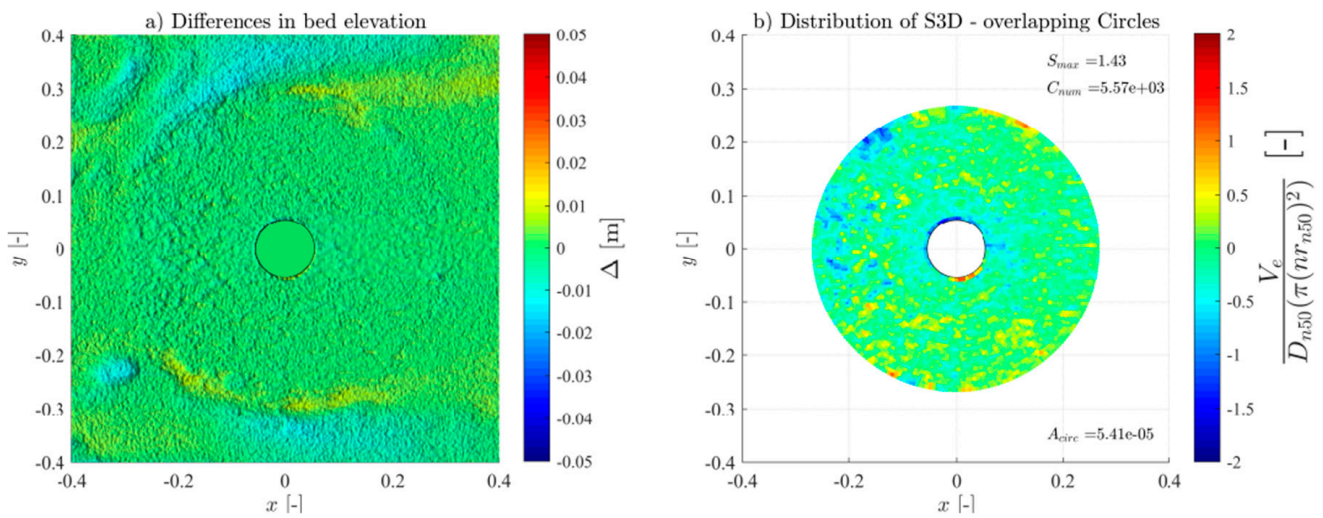


Figure A1. M_WC_7_1000 test: (a) DTM and (b) S_{3D} distribution—waves and currents from left to right.

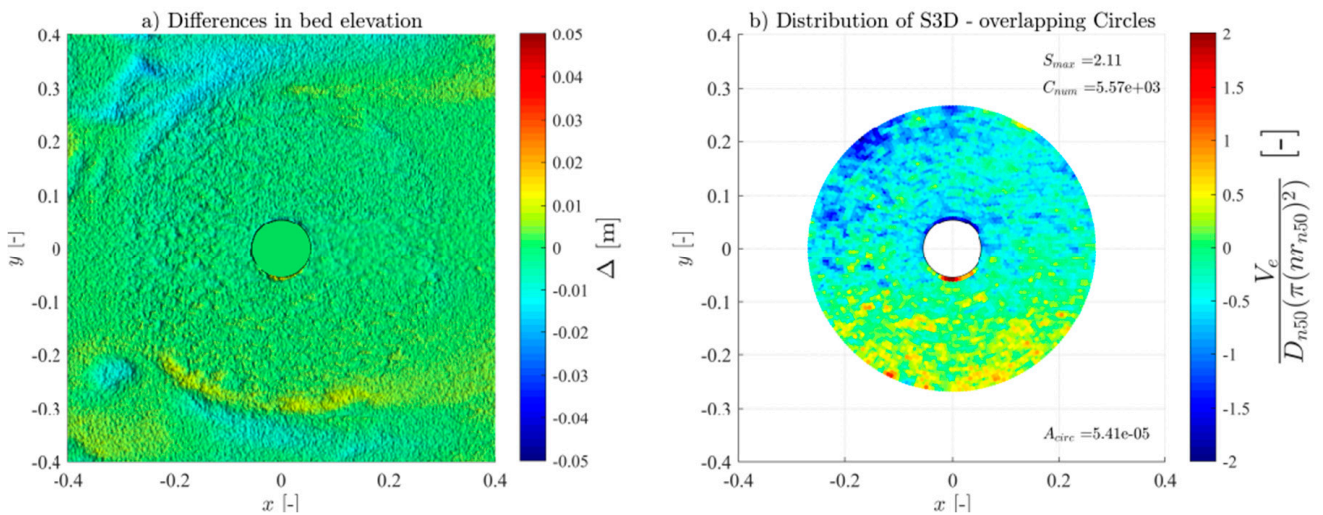


Figure A2. M_WC_7_2000: (a) DTM and (b) S_{3D} distribution—waves and currents from left to right.

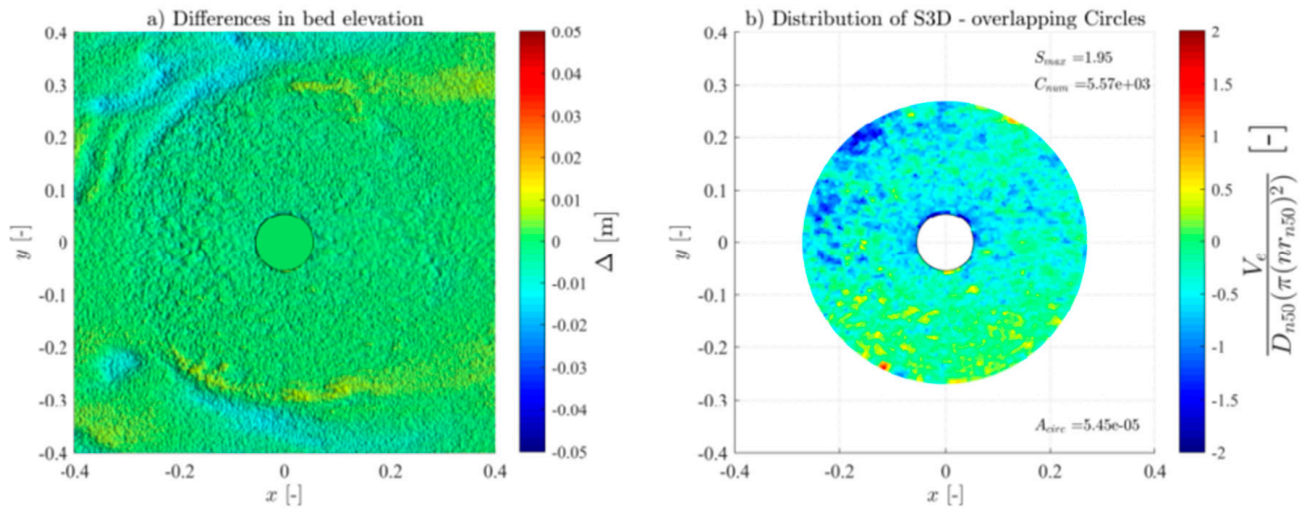


Figure A3. M_WC_7_3000 test: (a) DTM and (b) S_{3D} distribution—waves and currents from left to right.

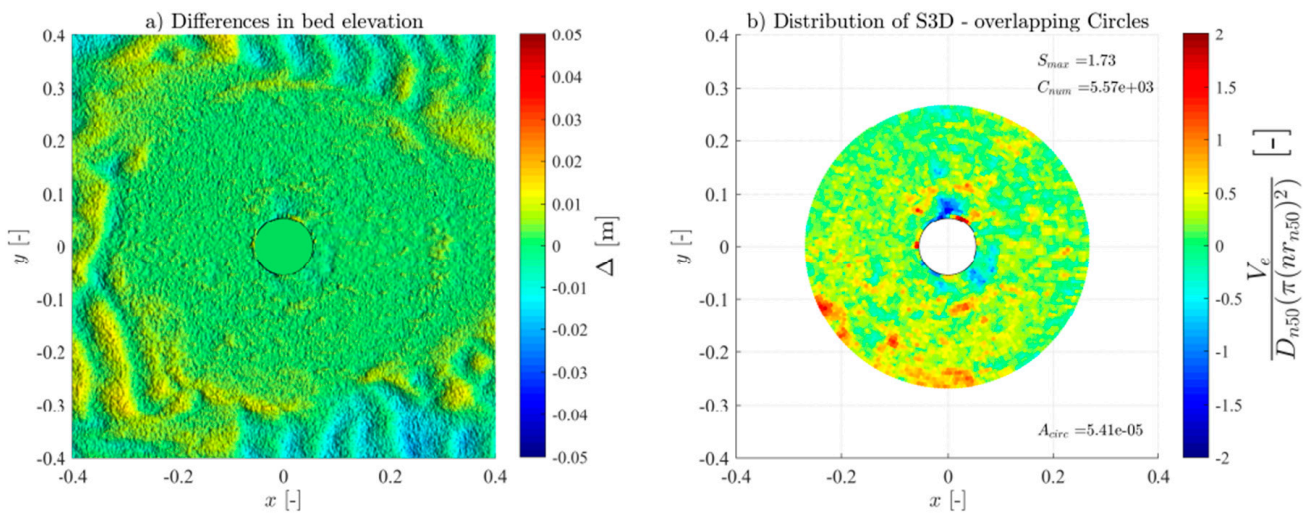


Figure A4. M_WC_11_1000 test: (a) DTM and (b) S_{3D} distribution—waves and currents from left to right.

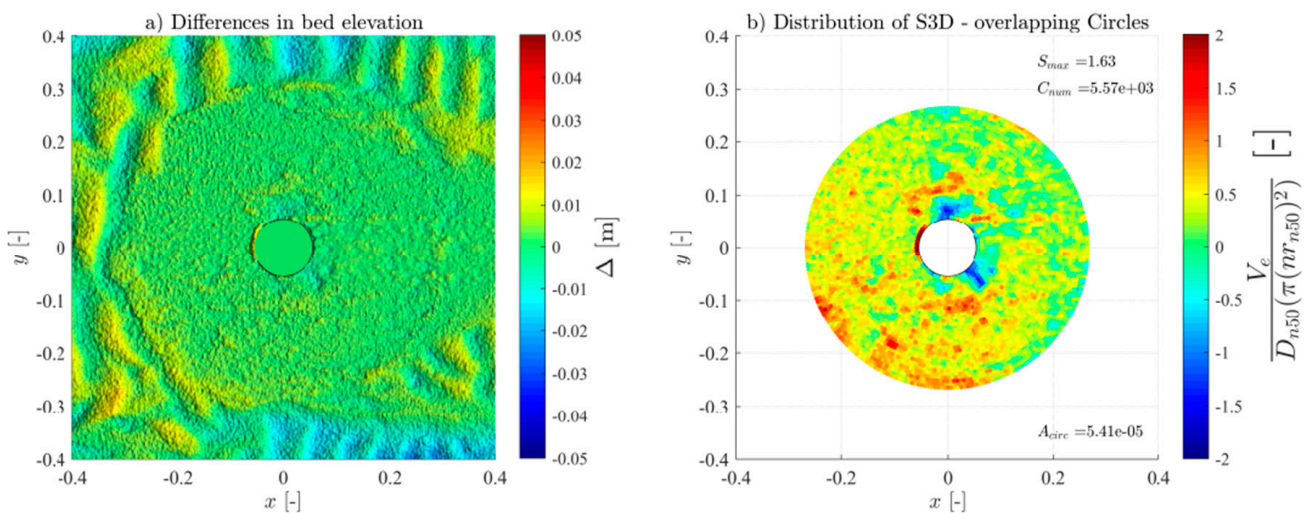


Figure A5. M_WC_11_2000 test: (a) DTM and (b) S_{3D} distribution—waves and currents from left to right.

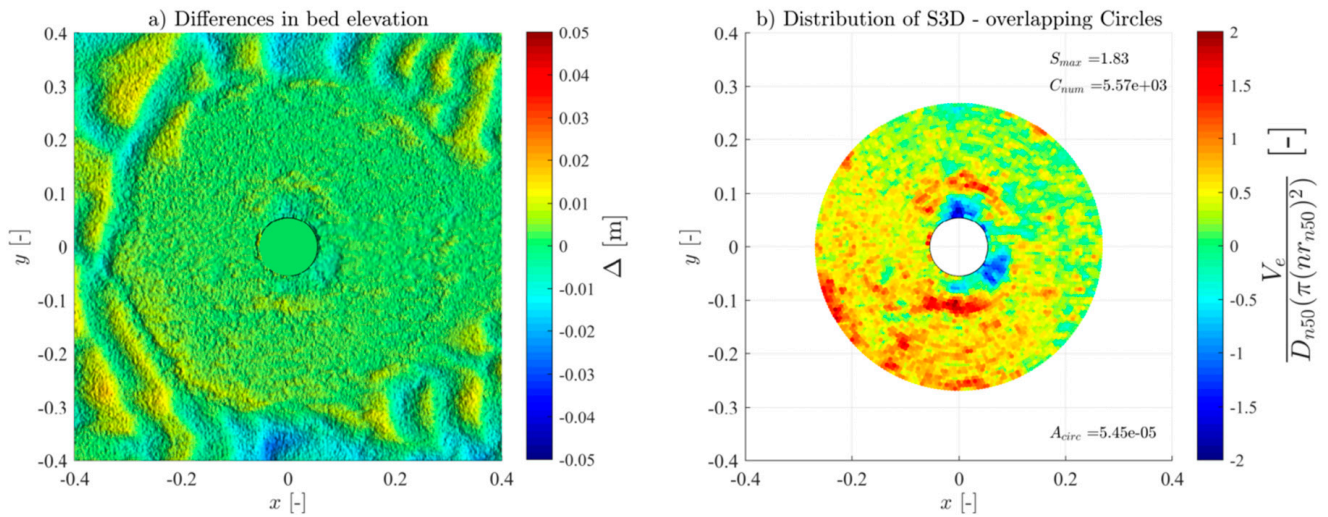


Figure A6. M_WC_11_3000 test: (a) DTM and (b) S_{3D} distribution—waves and currents from left to right.

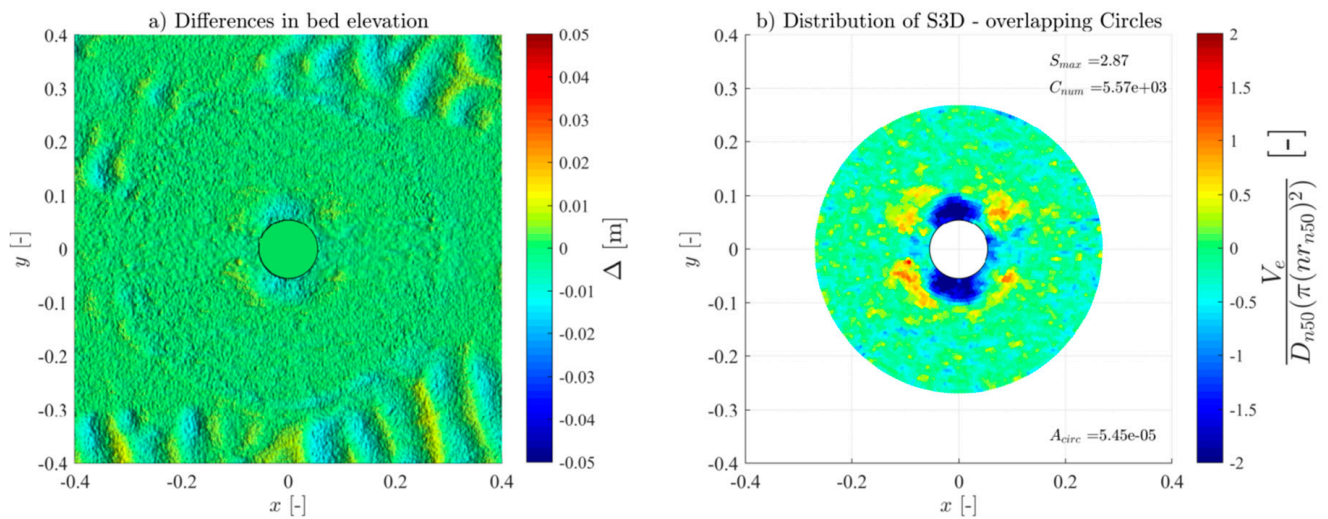


Figure A7. M_WC_15.5_1000 test: (a) DTM and (b) S_{3D} distribution—waves and currents from left to right.

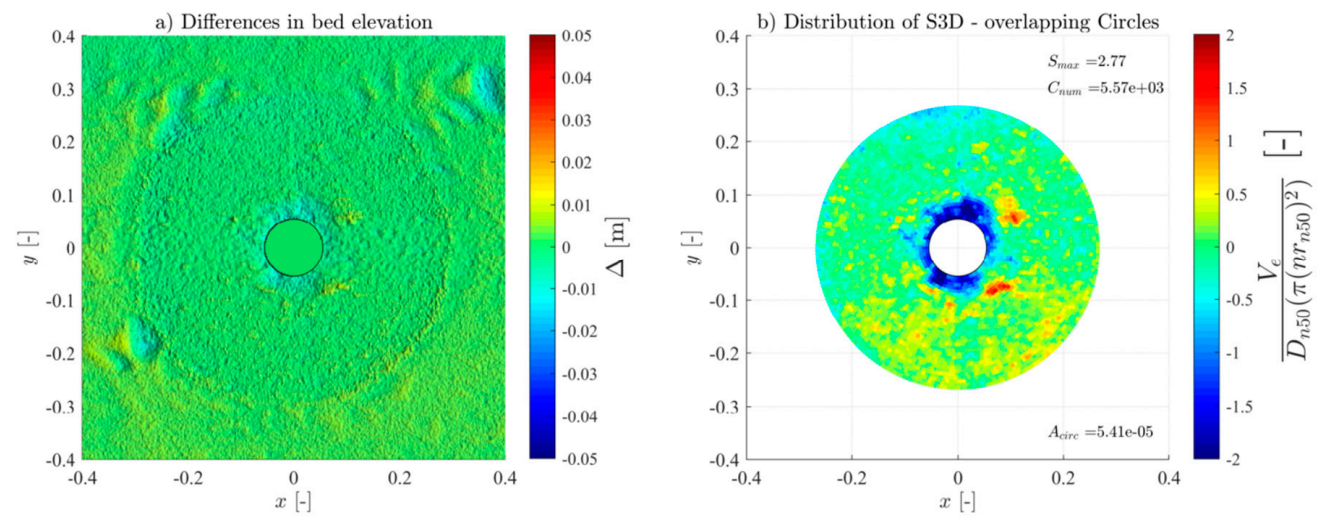


Figure A8. M_WI_14_1000 test: (a) DTM and (b) S_{3D} distribution—waves from left to right.

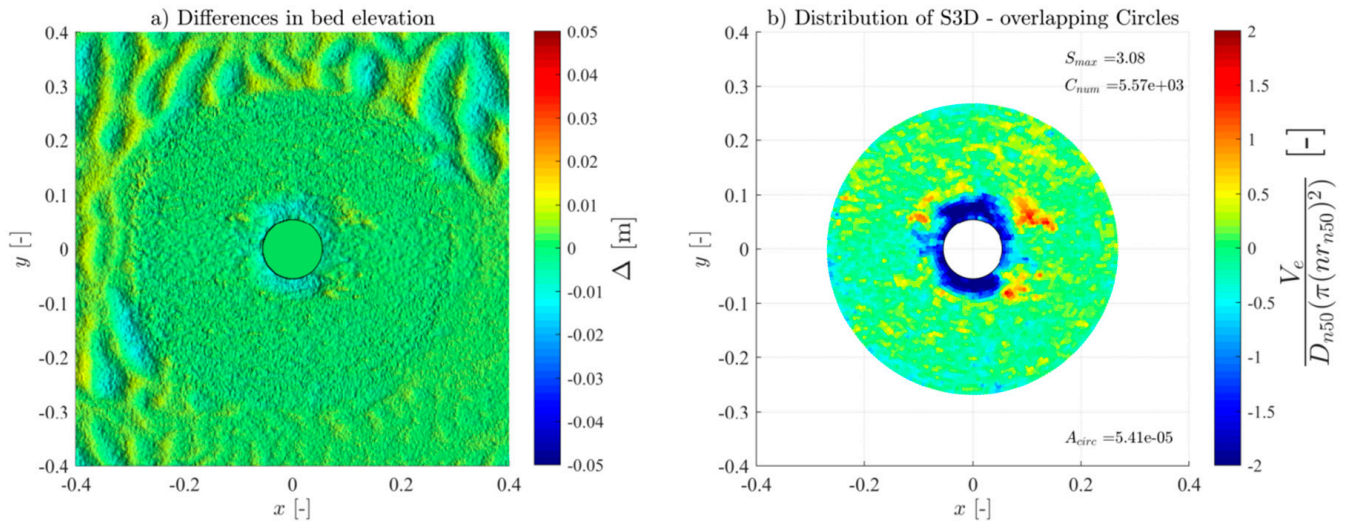


Figure A9. M_WI_14_2000: (a) DTM and (b) S_{3D} distribution—waves from left to right.

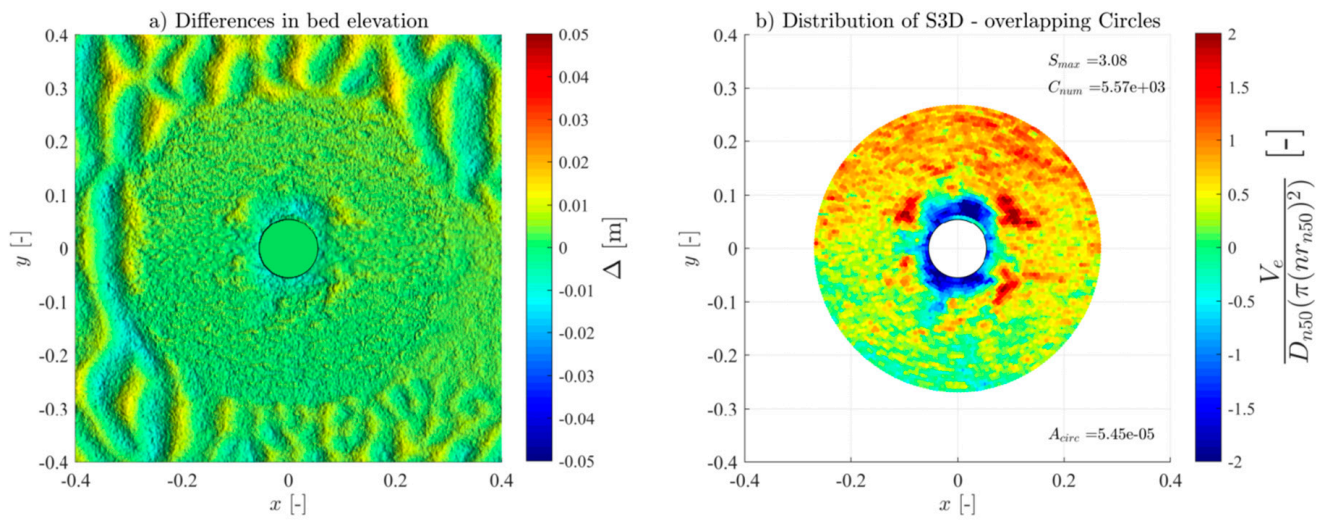


Figure A10. M_WI_14_3000 test: (a) DTM and (b) S_{3D} distribution—waves from left to right.

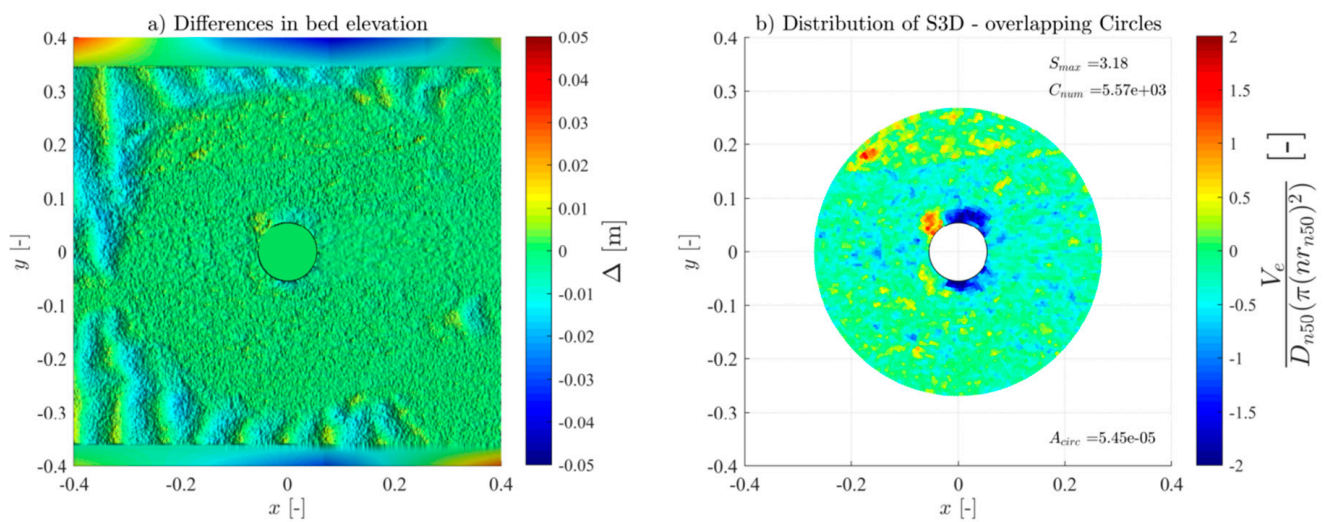


Figure A11. M_WR_14_1000 test: (a) DTM and (b) S_{3D} Distribution—waves from left to right.

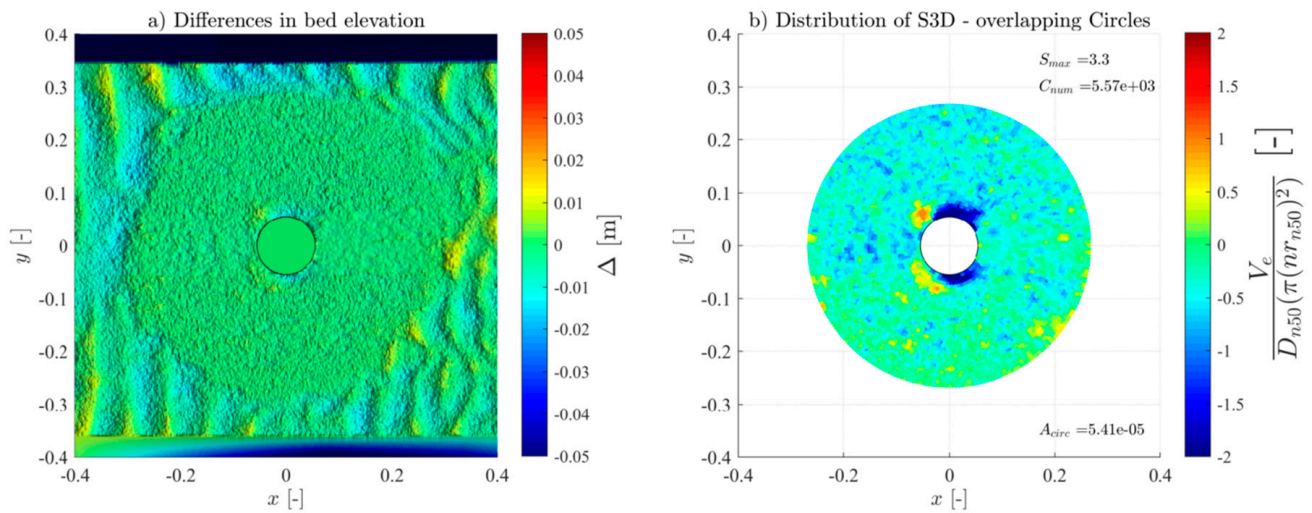


Figure A12. M_WR_14_2000 test: (a) DTM and (b) S_{3D} distribution—waves from left to right.

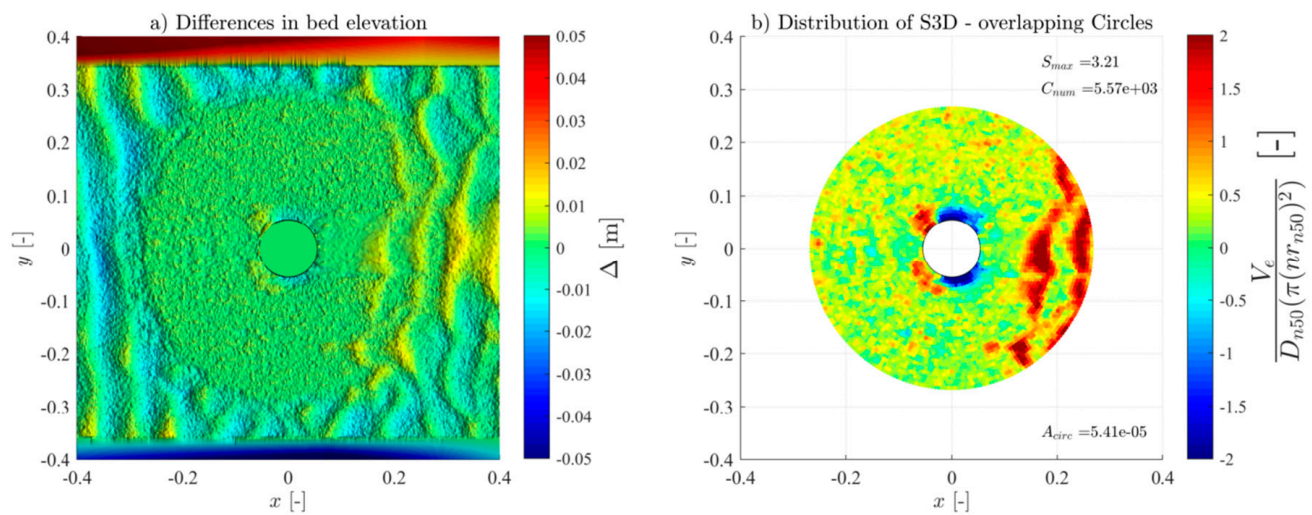


Figure A13. M_WR_14_3000 test: (a) DTM and (b) S_{3D} distribution—waves from left to right.

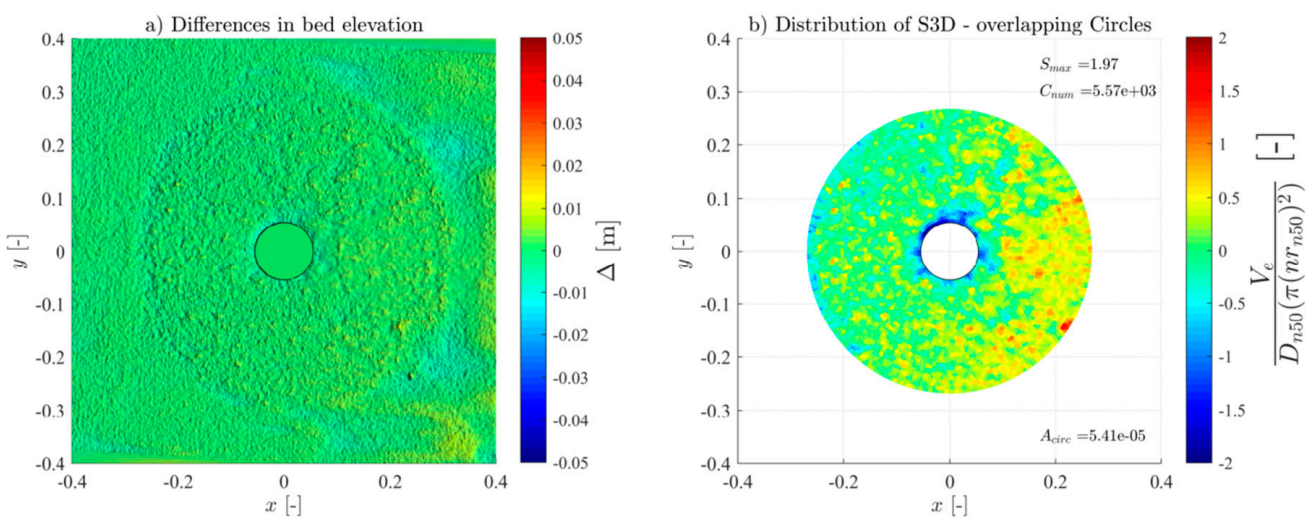


Figure A14. MH_WC_7_1000 test: (a) DTM and (b) S_{3D} distribution—waves and currents from left to right.

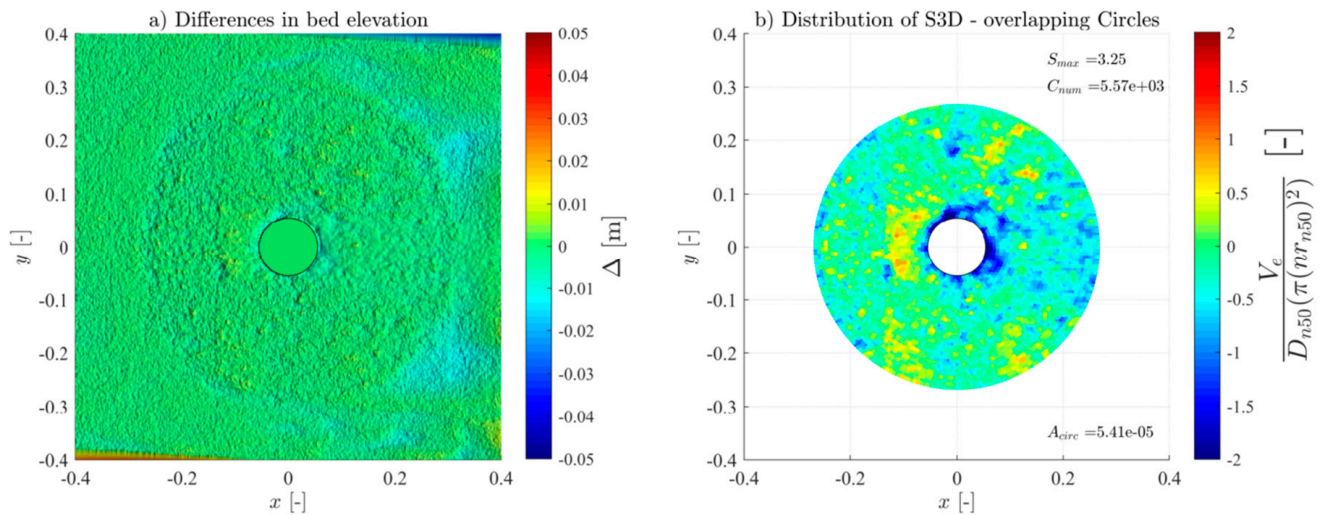


Figure A15. MH_WC_7_2000 test: (a) DTM and (b) S_{3D} distribution—waves and currents from left to right.

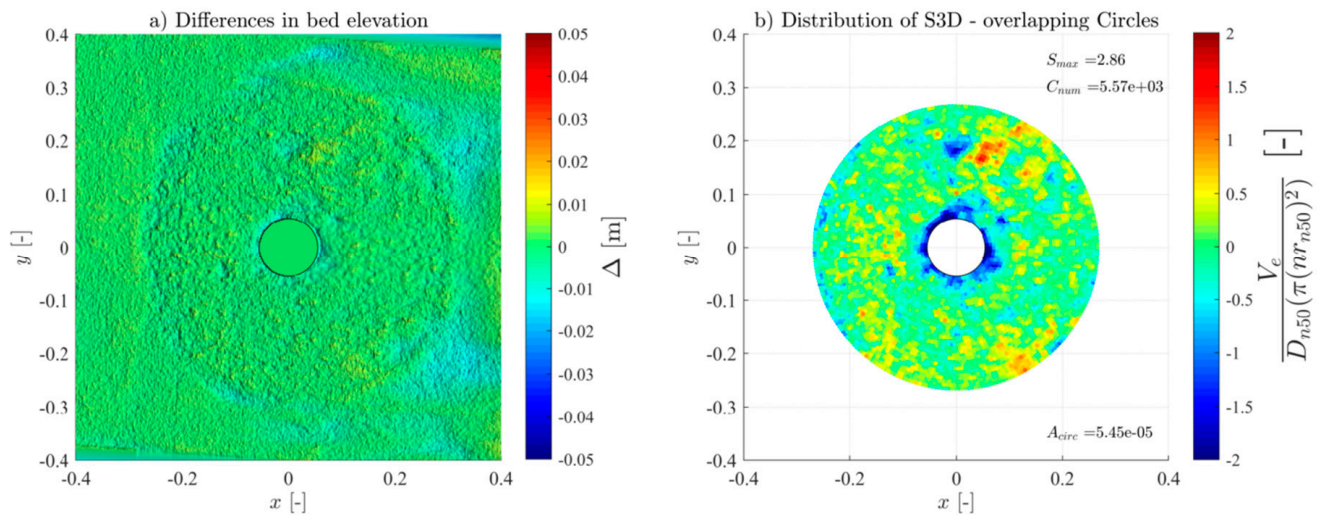


Figure A16. MH_WC_7_3000 test: (a) DTM and (b) S_{3D} distribution—waves and currents from left to right.

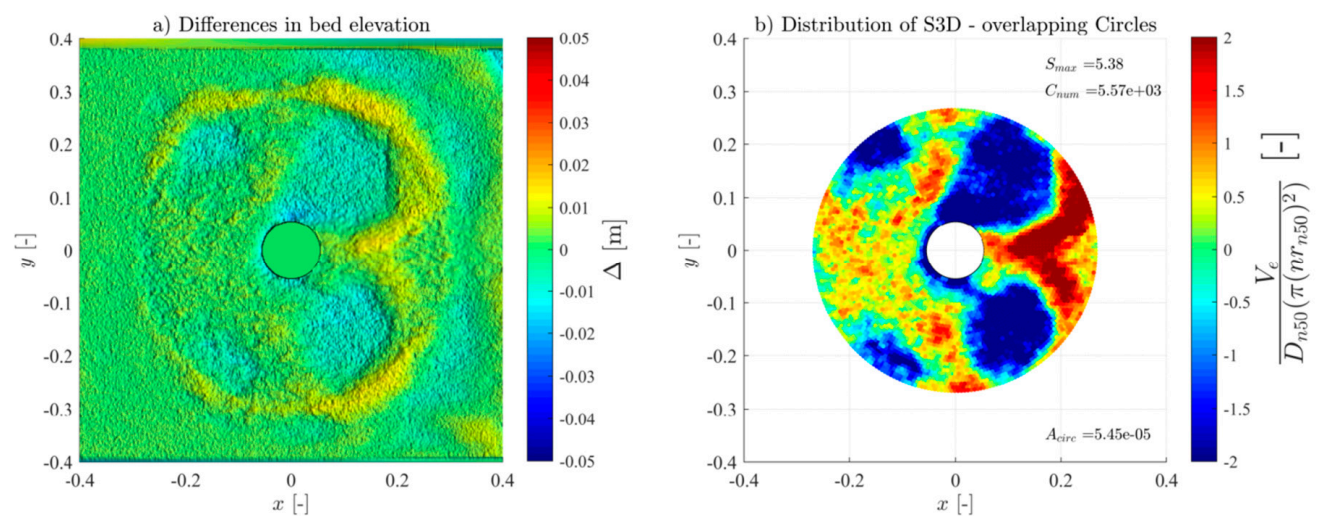


Figure A17. MH_WC_11_1000 test: (a) DTM and (b) S_{3D} distribution—waves and currents from left to right.

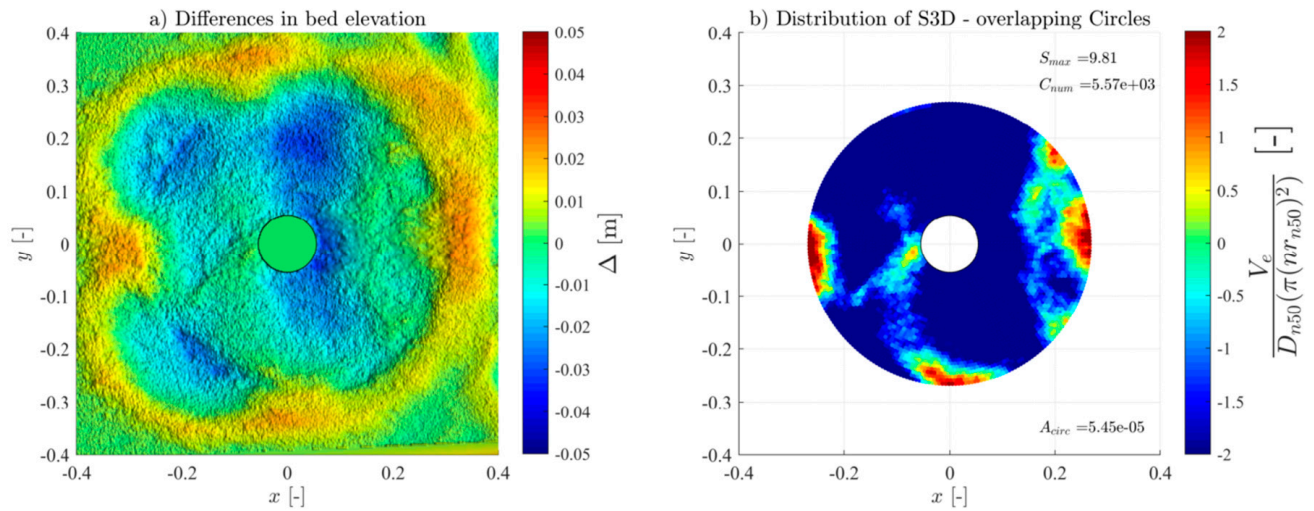


Figure A18. MH_WC_15.5_1000 test: (a) DTM and (b) S_{3D} distribution—waves and currents from left to right.

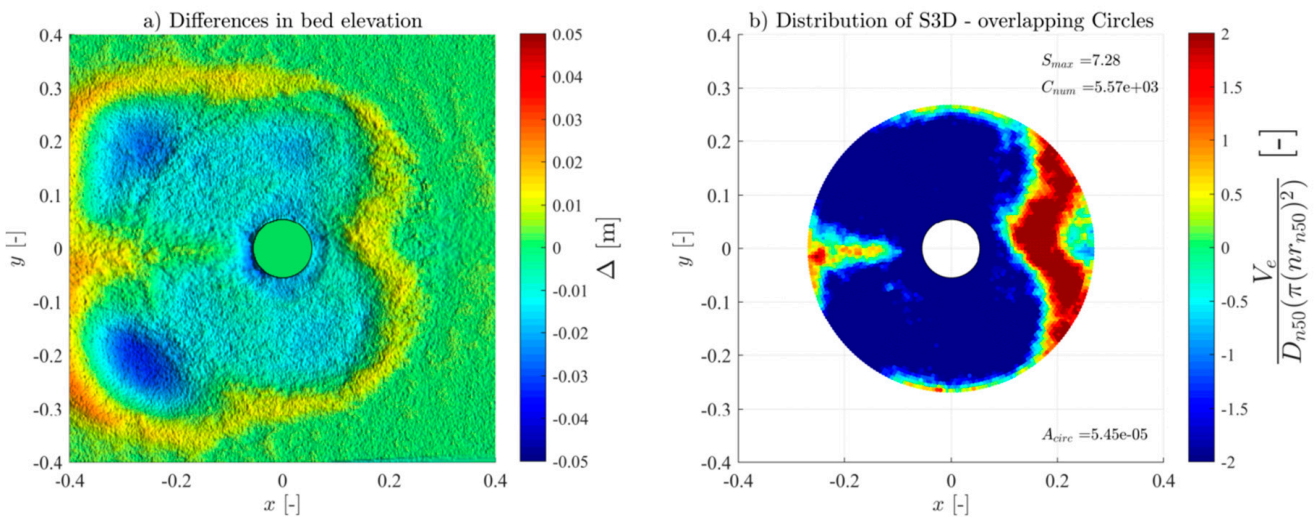


Figure A19. MH_WI_14_1000 test: (a) DTM and (b) S_{3D} distribution—waves from left to right.

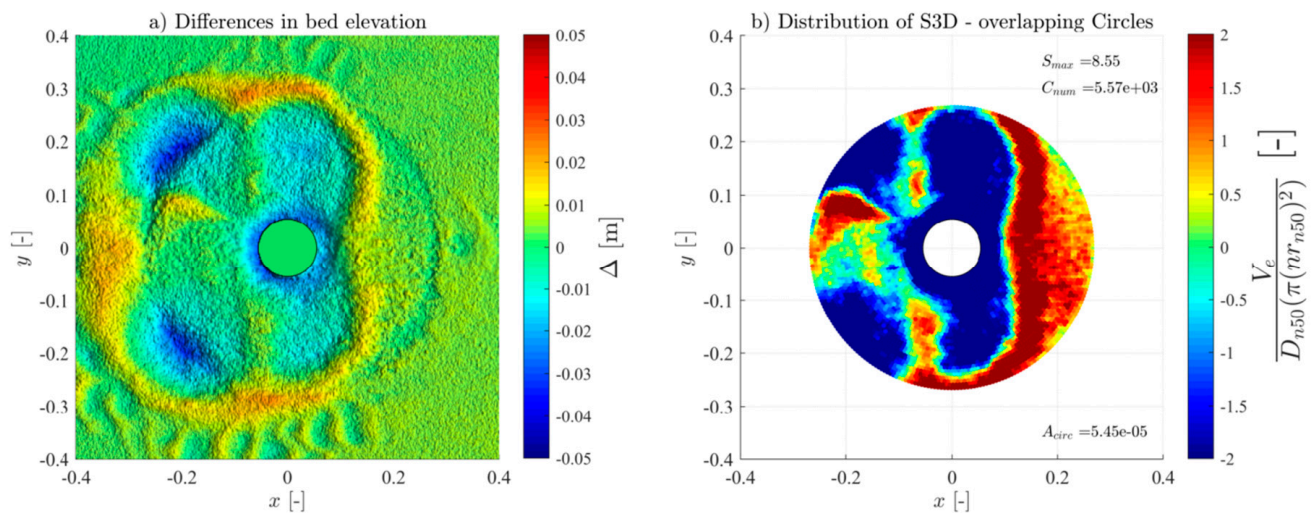


Figure A20. MH_WR_14_1000 test: (a) DTM and (b) S_{3D} distribution—waves from left to right.

Appendix B

Monopile and Hybrid Foundation S3D Results for Different Grid Ratios

Table A1. $S_{3D,measured}$ computation for different grid ratios—(A): M_WC_7_3000; (B): M_WC_11_3000; (C): M_WC_15.5_1000; (D): M_WI_3000; (E): M_WR_1000.

Monopile Tests						(A)	(B)	(C)	(D)	(E)
A_{sub}	Value [m ²]	$\eta_{S3D,grid}$	p Value	R_{circle} [m]	C_{num}	$S_{3D,measured}$				
D_{n50}^2	1.362×10^{-5}	1.000	1.1284	2.082×10^{-3}	23,200	3.46	2.71	3.96	3.42	5.26
$1.111D_{n50}^2$	1.513×10^{-5}	0.900	1.1894	2.194×10^{-3}	20,700	3.12	2.21	3.71	3.39	4.75
$1.5D_{n50}^2$	2.042×10^{-5}	0.667	1.3820	2.550×10^{-3}	15,400	3.03	2.49	3.71	3.36	4.77
$2D_{n50}^2$	2.723×10^{-5}	0.500	1.5958	2.944×10^{-3}	11,500	2.29	2.02	3.26	3.29	4.03
$3D_{n50}^2$	4.085×10^{-5}	0.333	1.9544	3.606×10^{-3}	7640	2.21	1.95	3.38	3.28	3.43
$4D_{n50}^2$	5.446×10^{-5}	0.250	2.2568	4.164×10^{-3}	5570	1.95	1.83	2.87	3.08	3.18
$5D_{n50}^2$	6.808×10^{-5}	0.200	2.5231	4.655×10^{-3}	4600	2.20	1.89	2.86	2.84	3.20
$6D_{n50}^2$	8.170×10^{-5}	0.167	2.7640	5.099×10^{-3}	3770	1.90	1.96	2.85	2.67	2.95
$7D_{n50}^2$	9.531×10^{-5}	0.143	2.9854	5.508×10^{-3}	3250	1.94	1.78	2.79	2.63	2.59
$8D_{n50}^2$	1.089×10^{-4}	0.125	3.1915	5.888×10^{-3}	2780	1.76	1.87	2.93	2.82	2.71
$9D_{n50}^2$	1.225×10^{-4}	0.111	3.3851	6.246×10^{-3}	2550	1.91	1.85	2.78	2.85	2.82
$10D_{n50}^2$	1.362×10^{-4}	0.100	3.5682	6.583×10^{-3}	2150	1.70	1.64	2.69	2.70	2.49
$16D_{n50}^2$	2.179×10^{-4}	0.063	4.5135	8.327×10^{-3}	1400	1.75	1.61	2.68	2.55	2.30
$20D_{n50}^2$	2.723×10^{-4}	0.050	5.0463	9.310×10^{-2}	1100	1.58	1.51	2.58	2.55	2.30
$25D_{n50}^2$	3.404×10^{-4}	0.040	5.6419	1.041×10^{-2}	839	1.36	1.56	2.64	2.50	1.91
$50D_{n50}^2$	6.808×10^{-4}	0.020	7.9788	1.472×10^{-2}	409	1.24	1.34	2.40	2.07	1.69
$100D_{n50}^2$	1.362×10^{-3}	0.010	11.2838	2.082×10^{-2}	189	1.04	1.03	2.03	1.95	1.43
A_{pile}	9.503×10^{-4}	0.00143	29.8103	5.500×10^{-2}	24	0.62	−0.02	0.52	0.31	0.60

Table A2. $S_{3D,measured}$ computation for different grid ratios—(A): MH_WC_7_3000; (B): MH_WC_11_1000; (C): MH_WC_15.5_1000; (D): MH_WI_1000; (E): MH_WR_1000.

Hybrid Monopile Tests						(A)	(B)	(C)	(D)	(E)
A_{sub}	Value [m ²]	$\eta_{S3D,grid}$	p Value	R_{circle} [m]	C_{num}	$S_{3D,measured}$				
D_{n50}^2	1.362×10^{-5}	1.000	1.1284	2.082×10^{-3}	23,200	3.22	5.88	10.7	8.79	12.1
$1.111D_{n50}^2$	1.513×10^{-5}	0.900	1.1894	2.194×10^{-3}	20,700	3.54	5.72	11.2	9.4	10.4
$1.5D_{n50}^2$	2.042×10^{-5}	0.667	1.3820	2.550×10^{-3}	15,400	3.31	5.97	11.4	8.64	10.9
$2D_{n50}^2$	2.723×10^{-5}	0.500	1.5958	2.944×10^{-3}	11,500	3.14	5.28	11.1	8.74	10.3
$3D_{n50}^2$	4.085×10^{-5}	0.333	1.9544	3.606×10^{-3}	7640	3.11	5.44	10.1	8.30	9.40
$4D_{n50}^2$	5.446×10^{-5}	0.250	2.2568	4.164×10^{-3}	5570	2.86	5.38	9.81	7.28	8.55
$5D_{n50}^2$	6.808×10^{-5}	0.200	2.5231	4.655×10^{-3}	4600	2.60	4.97	10.1	7.34	9.59
$6D_{n50}^2$	8.170×10^{-5}	0.167	2.7640	5.099×10^{-3}	3770	2.63	5.02	9.13	6.90	8.35
$7D_{n50}^2$	9.531×10^{-5}	0.143	2.9854	5.508×10^{-3}	3250	2.60	4.80	8.88	7.11	8.49
$8D_{n50}^2$	1.089×10^{-4}	0.125	3.1915	5.888×10^{-3}	2780	2.68	4.68	9.12	7.00	8.04
$9D_{n50}^2$	1.225×10^{-4}	0.111	3.3851	6.246×10^{-3}	2550	2.49	4.87	8.96	6.79	8.57

Table A2. Cont.

Hybrid Monopile Tests						(A)	(B)	(C)	(D)	(E)
A _{sub}	Value [m ²]	$\eta_{S3D,grid}$	p Value	R _{circle} [m]	C _{num}	S _{3D,measured}				
10D _{n50} ²	1.362×10^{-4}	0.100	3.5682	6.583×10^{-3}	2150	2.32	5.03	8.97	6.59	8.21
16D _{n50} ²	2.179×10^{-4}	0.063	4.5135	8.327×10^{-3}	1400	2.16	4.95	8.68	6.38	7.75
20D _{n50} ²	2.723×10^{-4}	0.050	5.0463	9.310×10^{-3}	1100	1.93	4.71	8.54	6.43	7.15
25D _{n50} ²	3.404×10^{-4}	0.040	5.6419	1.041×10^{-2}	839	1.95	4.39	8.41	6.38	7.48
50D _{n50} ²	6.808×10^{-4}	0.020	7.9788	1.472×10^{-2}	409	1.41	4.20	8.24	6.04	6.37
100D _{n50} ²	1.362×10^{-3}	0.010	11.2838	2.082×10^{-2}	189	1.20	3.56	8.16	5.37	5.77
A _{pile}	9.503×10^{-4}	0.00143	29.8103	5.500×10^{-2}	24	0.30	2.22	7.06	3.69	3.45

Appendix C

MATLAB Function for Calculating S/D_p , $K_{c_{tot}}$, and MOB_{tot} —Using Formulas Developed by [21,42]

```
function [S_over_Dp]=S_over_Dp(temp, rho_s, rho_w, dn50, Hs, Tp, Uc, Um, hw, Dp,
ts, L, alpha_deg)
%% Extract input parameters from the structure
% temp = water temperature (°C);
%rho_s = mass density armour layer (kg/m³);
%rho_w = water density (kg/m³);
%dn50 = nominal stone diameter (m);
%Hs = significative wave height (m) measured in the tests;
%Tp = peak period (s) measured in the tests;
%Uc = current velocity (m/s) measured in the tests;
%Um = orbital wave velocity (m/s) measured in the tests;
%hw = water depth (m);
%h_top = water depth at the top of protection (m);
%Dp = pile diameter (m);
%ts = armour layer thickness in units (relative to the Dn50 value)
%L = wavelength (m) calculated using Wiberg and Sherwood (2008);
%alpha_deg = wave-current degree angle (°);

%% A.1: Constants
g = 9.81; % gravity

%% A.2: Kinematic viscosity
nu = (1.14-0.031*(temp-15) + 0.00068*(temp-15)^2) * 1e-6;

%% A.3: Rock properties
d50 = dn50/0.84;
h_top = hw-(ts * dn50);
Delta_s = (rho_s-rho_w)/rho_w; % specific density
d_star = d50 * (((Delta_s * g)/(nu^2))^(1/3)); %dimensionless particle diameter

% Shields critical parameter
theta_cr = 0.055 * (1-exp(-0.02 * d_star)) + 0.3 / (1 + 1.2 * d_star);
```

```

% Roughness height
ks = 2.5 * d50;

%% A.4: Current-related parameters
z0 = ks/30; % bed roughness length
CD = (0.4/(log(hw/z0)-1))^2; % drag coefficient
u_star_c = sqrt(CD) * Uc; % current-related shear velocity
tau_c = rho_w * u_star_c^2; % current-related shear stress
theta_c = tau_c/((rho_s-rho_w) * g * d50); % current-related Shields parameter
MOBc = theta_c/theta_cr; % current-related relative mobility
KCc = (Uc * Tp)/Dp; % current-related KC number

%% A.5.1: Correction factor K_top for velocity at top of scour
K_top = sinh((2 * pi * hw)/L)/sinh((2 * pi * h_top)/L); % correction factor for orbital
velocity on top of scour protection
uw_top = K_top * Um; % wave velocity at top
Aw_top = (uw_top * Tp)/(2 * pi); % wave orbital motion amplitude on top of scour
protection

%% A.5.2: Wave friction factor
A_ks = Aw_top/ks;
if A_ks > 0.2 && A_ks < 2.92
    fw = 0.32 * A_ks^(-0.8);
elseif A_ks >= 2.92 && A_ks < 727
    fw = 0.237 * A_ks^(-0.52);
elseif A_ks >= 727
    fw = 0.04 * A_ks^(-0.25);
else
    error('Awa/ks value must be greater than 0.2 for valid friction factor calculation.');
```

```

end

%% Wave shear velocity and stress
u_star_w = (sqrt(0.5 * fw)) * uw_top; % wave-related shear velocity
tau_w = rho_w * u_star_w^2; % wave-related bed shear stress
theta_w = tau_w/((rho_s-rho_w) * g * d50); % wave-related shields parameter
MOBw = theta_w/theta_cr; % wave-related relative mobility
KCw = (uw_top * Tp)/Dp; % wave-related KC number

%% A.6: Combined shear stress and mobility
tau_m = tau_c + 1.2 * tau_c * ((tau_w/(tau_c + tau_w))^3.2); % Mean combined current-
and wave-related bed shear stress
alpha_rad = deg2rad(alpha_deg); % angle between waves and currents
tau_max = sqrt(tau_m^2 + tau_w^2 + 2 * tau_w * tau_m * cos(alpha_rad)); % max
combined current- and wave-related bed shear stress
theta = tau_max/((rho_s-rho_w) * g * d50); % combined current- and wave-related
Shields parameter
MOB = theta/theta_cr; % combined current- and wave-related relative mobility

```



```

%% Compute KC_tot (Keulegan–Carpenter number)
KC_tot = ((uw_top + Uc) * Tp)/Dp;

%% Compute S/Dp (final equation)
S_over_Dp_value = (1 + (3.93/(1 + exp(−0.74 * KC_tot + 4.75)))) * 0.07 * (MOB^(1.65));
% relative scour depth

%% Display results

fprintf('\n');
fprintf('KCtot: %.3f\n', KC_tot);
fprintf('KCc: %.3f\n', KCc);
fprintf('KCw: %.3f\n', KCw);
fprintf('\n');
fprintf('MOB: %.3f\n', MOB);
fprintf('MOBc: %.3f\n', MOBc);
fprintf('MOBw: %.3f\n', MOBw);
fprintf('\n');
fprintf('kinematic viscosity: %.3e\n', nu);
fprintf('delta_s: %.3f\n', Delta_s);
fprintf('D*: %.3f\n', d_star);
fprintf('\n');
fprintf('theta: %.3f\n', theta);
fprintf('theta_cr: %.3f\n', theta_cr);
fprintf('theta_c: %.3f\n', theta_c);
fprintf('theta_w: %.3f\n', theta_w);
fprintf('\n');
fprintf('tau_c: %.3f\n', tau_c);
fprintf('tau_w: %.3f\n', tau_w);
fprintf('tau_medio: %.3f\n', tau_m);
fprintf('tau_maximo: %.3f\n', tau_max);
fprintf('\n');
fprintf('ks: %.3f\n', ks);
fprintf('z0: %.3e\n', z0);
fprintf('CD: %.3f\n', CD);
fprintf('u*c: %.3f\n', u_star_c);
fprintf('u*w: %.3f\n', u_star_w);
fprintf('uw_top: %.3f\n', uw_top);
fprintf('Ktop: %.3f\n', K_top);
fprintf('Awtop: %.3f\n', Aw_top);
fprintf('A/ks: %.3f\n', A_ks);
fprintf('fw: %.3f\n', fw);
fprintf('\n');
fprintf('S/D: %.3f\n', S_over_Dp_value);

end

```

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Appendix IV – Chambel *et al.* (2026a)

Article

Damage Characterisation of Scour in Riprap-Protected Jackets and Hybrid Foundations

João Chambel ^{1,2,*} , Tiago Fazerres-Ferradosa ^{1,2} , Mahdi Alemi ³ , Francisco Taveira-Pinto ^{1,2} 
and Pedro Lomonaco ⁴ 

¹ Department of Civil Engineering and Georesources, Faculty of Engineering, University of Porto (FEUP), Rua Dr. Roberto Frias s/n, 4200-465 Porto, Portugal; tferradosa@fe.up.pt (T.F.-F.); fpinto@fe.up.pt (F.T.-P.)

² Marine Energy and Hydraulic Structures Research Group, Interdisciplinary Centre of Marine and Environmental Research (CIIMAR-LA), University of Porto (FEUP), Port of Leixões Cruise Terminal, Av. General Norton de Matos s/n, 4450-208 Matosinhos, Portugal

³ IMDC, Van Immerseelstraat 66, 2018 Antwerp, Belgium

⁴ O.H. Hinsdale Wave Research Laboratory, College of Engineering, Oregon State University (OSU), Corvallis, OR 97331, USA; pedro.lomonaco@oregonstate.edu

* Correspondence: up201304674@fe.up.pt

Abstract

The global transition towards sustainable energy has accelerated the development and deployment of offshore wind turbines. Jacket foundations, commonly installed in intermediate to deep water depths to access available space and higher load capacities, are built to withstand intensified hydrodynamic loads. Due to their structural complexity near the seabed, however, they are prone to local and global scour, which can compromise stability and increase maintenance costs. While extensive research has addressed scour protections around monopiles, limited attention has been given to complex foundation geometries or even hybrid configurations that combine energy-harvesting devices with structural support. These hybrid systems introduce highly unsteady flow fields and amplified turbulence effects that current design frameworks appear to be unable to capture. This study provides an experimental characterisation of scour damage in riprap-protected jackets as well as additional tests for a hybrid jacket foundation. A novel adaptation of a high-resolution overlapping sub-area methodology was employed. For the first time, it was successfully applied to quantify the damage to riprap protections for a complex offshore foundation. Results revealed that, although hybrid jackets showed the capacity to attenuate incident waves, the scour protection experienced damage numbers (S_{3D}) two to six times higher than conventional jackets due to flow amplifications. The findings highlight the need for revised design guidelines that can account for the complex hydrodynamic-structural interactions of next-generation marine harvesting technologies integrated into complex foundations.

Keywords: offshore renewable energy; scour protection; jackets; wave energy converter; hybrid foundations



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1. Introduction

Offshore wind energy (OWE) is a significant contributor to the global energy transition, and the European Union has identified the sector as a key component in achieving climate neutrality by 2050 [1]. It has expanded rapidly in recent years, driven by competitiveness, technological maturity, increasing efficiency, and a steady reduction in the Levelized

Cost of Energy (LCoE). For fixed offshore wind foundations (OWFs), scour represents a critical challenge that may compromise structural stability [2]. Riprap scour protections are commonly applied as countermeasures but represent a substantial share of the investment costs [3]. Optimising design guidelines is essential for achieving economic competitiveness while maintaining structural safety.

The concept of dynamic scour protection marked a significant advance over the well-established but conservative static approach. Dynamic protection depends on the size, geometry, layer thickness, and reshaping capacity of the armour layer units. The design is based on the damage number (Equation (1)), which was introduced by [4,5].

$$\frac{S_{3D}}{N^{b_0}} = a_0 \frac{U_m^3 T_{m-1,0}^2}{\sqrt{gd}(s-1)^{3/2} D_{n50}^2} + a_1 \left(a_2 + a_3 \frac{(U_c/w_s)^2 (U_c + a_4 U_m)^2 \sqrt{d}}{g D_{n50}^{3/2}} \right) \quad (1)$$

where N is the number of waves, g is the gravitational acceleration, d is the water depth, U_m is the wave orbital velocity, $T_{m-1,0}$ is the energy wave period, s is the ratio between ρ_s and ρ_w , U_c is the current depth-average velocity, w_s is the settling velocity, a_0 , a_2 , a_3 and b_0 are regression coefficients equal to 0.00076, -0.022 , 0.0079 , and 0.243 , respectively, and a_1 and a_4 are coefficients for hydrodynamic conditions [5].

Unlike the static approach, based on critical shear stress [6,7], the dynamic design approach enables these limitations to be surpassed while providing less expensive alternatives by using rubble-mound material with a lower nominal diameter (D_{n50}). This reduces costs associated with materials, transport, and installation [2]. However, the S_{3D} -based design approach is limited by a lack of diverse datasets, its focus on monopiles, and the restricted range of water depths and layer thicknesses used within the study by [5]. Later studies by [8–10] expanded the testing conditions and reported overlapping situations regarding stability limits, with failure occurring above the threshold of $S_{3D} = 1.0$.

Presently, research related to scour and scour protection at complex-geometry and hybrid foundations has gained momentum. However, existing scour protection design approaches often neglect the structural complexity features of these foundations. Jackets have emerged as a consensus choice for increased water depths or locations with increased hydrodynamic conditions, due to their lightweight construction, higher stability, and adaptability under more intense hydrodynamic conditions [11–15]. According to [16], approximately 10% of the offshore wind turbines in Europe utilise jackets as their foundations. The bracings, joints, and secondary elements alter hydrodynamics by creating blockage effects, flow contractions, enhanced turbulence, and sediment transport gradients (Figure 1), leading to significant local scour [17]. Several experimental studies [13–15,18–24] aimed to contribute to an improved understanding of the complex scouring process at jackets, with some studies even comparing these interactions to those in monopiles.

The research conducted by [19] showed that the equation developed by [25] was inadequate for predicting local scour around jacket-type foundations. The authors propose an empirical formulation to estimate the end scour depth (S_{end}) under combined perpendicular wave-current loading at the piles, introducing structural parameters to represent the effects of flow obstruction that depend on the jacket leg position. Regarding temporal scour development, it was shown that the relationship between U_{cw} (wave-current velocity ratio) and T^* (dimensionless time scale) differs significantly for the rear piles compared to a monopile. However, no method was provided to quantify this difference. It was further reported that in wave-dominated regimes, scour protections should be designed locally for each pile or reinforced with a higher thickness [20]. In contrast, in current-dominated regimes, protections should be extended across the entire footprint area. Additionally, a set of formulas was proposed to estimate the spatial global scour pattern, defined as the cumulative dimensionless erosion volume ($V_{A,i}$), that enabled the quantification of eroded

sediment volume over a specific area. This parameter can be directly converted into a mean scour depth, described as incremental erosion depth ($D_{V,i}$), normalised over the jacket pile's diameter (D_{jacket})—the equivalent of S/D (relative scour depth) for monopiles.

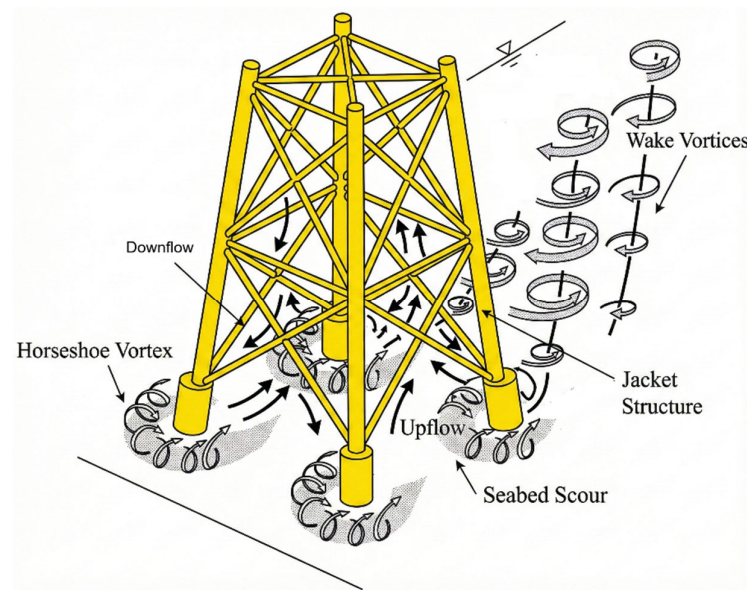


Figure 1. Scour Patterns in a jacket foundation.

According to [21], minor variations in node elevation or brace distance can significantly affect scour depth and extent. It also shown that scour behaviour differs under different hydrodynamic regimes, highlighting the importance of structural geometry in estimating scour and in designing scour countermeasures. More recently, ref. [22] observed that under clear-water conditions, when the upstream shear stress is insufficient to initiate sediment motion, the flow was diverted outwards, producing higher scour rates at the outer pile edges. However, under live-bed conditions, when the upstream shear stress exceeds the critical shear stress, resulting in continuous sediment transport, flow acceleration beneath and between the structure truss became more prominent, shifting scour towards the inside edge of the piles.

The current-only tests conducted by [14] found that maximum scour occurs at the upstream piles, where the upper truss induces strong flow disturbances. In contrast, kinetic energy dissipation and sediment deposition result in lower scour depths on the leeside of the piles. The study showed that scour tends to increase with U_c , and for constant current velocity, scour may also increase for increased water depths. The research performed by [23] extended the work conducted by [14], using regular-wave-only conditions for the same structure, reporting that scour dynamics depend strongly on wave characteristics. Larger wave heights and periods enhanced near-bed velocities and scour rates, whereas increasing water depths reduced scour due to weaker wave-seabed interactions. Additionally, shorter wave periods promoted deeper scour holes in the upstream piles. In comparison, longer periods shifted maximum scour depths downstream of the piles, due to delayed interaction with the upper truss. Based on these studies, ref. [15] investigated combined wave-current conditions and found that the resulting flow fields exhibit strong non-linear characteristics. Scour was found to increase with both the Keulegan-Carpenter number (KC), as defined in Equation (2), and U_{cw} . Higher U_{cw} values shifted the dominant flow patterns from streamline contractions and wake vortices to horseshoe vortices. Moreover, while scour

rates consistently increased with KC under clear-water conditions, in live-bed regimes, scour first increased and then decreased with higher KC values.

$$KC = \frac{U_m \cdot T_p}{D_{jacket}} \quad (2)$$

An equation developed by [24] was proposed to refine the prediction formula established by [19], emphasising the importance of additional experimental data in developing robust prediction methods.

Regarding scour depth comparisons between jackets and monopiles, ref. [19] compared their jacket experimental test results with those from monopile tests by [26], noting that lower scour rates were observed for jackets under similar conditions. However, opposite findings were reported by [14,23], as scour depths were found to be higher in jackets. These different observations highlight the uncertainty regarding the structural complexity of jacket foundations, leading [24] to conclude that geometrical features (structure transparency, pile distance/distribution, node distance to seabed), sediment characteristics, and hydrodynamic parameters— U_c , U_m , U_{cw} , KC , water depth, and relative angle between waves and currents—are paramount to develop more accurate equations for such complex foundations.

Collectively, studies found in the literature address key scour parameters, including S/D , scour extent/width, T^* , S_{eq} (equilibrium scour depth), eroded volumes and areas, and scour behaviour under current-, wave-, and wave-current regimes. Although scour protections were not considered, the findings provide valuable guidance for creating future design guidelines by identifying scour patterns, depths, and volumes, thereby indicating where reinforcement is more critical. Comparisons to in situ measurements showed good levels of correspondence, supporting the reliability of the findings [27–29].

With the growing interest in these foundations, efforts have been made to develop scour protection design equations, since monopile-based formulations inaccurately predict and capture the damage around complex geometries. Therefore, some studies have tested scour protections for three-leg and four-leg jackets [13,30,31]. However, no universal guidelines were derived for the design of riprap scour protection systems.

The situation becomes even more severe when hybrid foundations are considered, as the interaction between the energy converters and the structural complexity of the foundations introduces additional challenges and uncertainties. Nonetheless, despite new risks associated with scour, instability, fatigue, and differential settlements, hybrid structures can improve energy yield per site per structure. To date, the application of scour protections to hybrid configurations remains unexplored, and the real effects of converter dynamics on the protection performance represent a significant knowledge gap [32]. A comparative analysis was provided by [33], evaluating riprap-protected monopiles against hybrid monopiles by incorporating an OSWEC. While the converter showed promise in incident hydrodynamics attenuation, its oscillatory motion substantially altered the local flow patterns (downflow, horseshoes, and lee-wake vortices), bed shear stresses, and pore pressure acting on the seabed and in the protection's armour layer.

To help advance this field of research, the present study provides a comparative analysis of a square riprap scour countermeasure applied to both a four-leg jacket and a hybrid jacket. The S_{3D} was predicted for different wave-current combinations, Equation (1), and then compared to the measured damage using a modified version of the overlapping-circle method developed by [34], which is used to characterise the damage in rubble-mound

protections for marine and coastal structures, as a function of the eroded volume in each sub-area circle of the analysed mesh (Equation (3)).

$$S_{3D} = \frac{V_{e,circle}}{D_{n50} \cdot \pi R_{circle}^2} \quad (3)$$

A thorough analysis of all variables, including an examination of other empirical formulations for scour and deposition, was conducted to enhance insights that could aid in future extensions and generalisations of scour protections for complex structures. The results showed that existing monopile-based criteria, as defined by [4,5], fail to predict damage for complex foundations. For the jacket tests, the protection remained stable or presented dynamic behaviour without failure. In contrast, for most cases, the hybrid jackets exhibited irreversible damage to the armour layer due to pressure variations caused by the converter's oscillatory motion, associated with enhanced flow patterns.

The authors acknowledge the importance of the topic to understand how scour, damage, and hydrodynamic interactions develop around complex and hybrid structures. Some of the core innovations and contributions presented in this study are summarised as follows:

- It establishes a thorough experimental campaign that applies riprap scour protections designed according to recommendations found in the literature to the entire footprint area of a jacket foundation, to evaluate their performance and to compare the damage results with existing design criteria, developed for monopile foundations.
- Performs one of the first physical model tests on protected hybrid jackets, by coupling an OSWEC to the foundation, comparing them to the jacket results to highlight disparities, to demonstrate how the OSWEC paddle's oscillatory motion can modify the governing mechanisms of scour, influence turbulence, hydrodynamics, and be a key driver of armour-layer damage.
- Presents and successfully applies a novel adaptation of the overlapping-circle method suitable for complex foundations, allowing for improved analysis of damage distribution, as the use of fixed sub-areas often overlooks damage occurring in intersection sub-area zones.
- Suggests alternative metrics presented by [33] to better quantify and evaluate the performance of scour protections in complex offshore settings, which may successfully identify the correct protection behaviour.

The results and insights provided in this research regarding the design, applicability, and performance of riprap protections are expected to aid in the development of more effective scour mitigation strategies, thereby highlighting the need for design approaches that account for a broader range of offshore and marine infrastructures.

2. Materials and Methods

2.1. Experimental Setup

Experiments were conducted in a 29 m long, 1 m wide, and 1 m deep wave-and-current flume (Figure 2) at the Hydraulics Laboratory of the Hydraulics, Water Resources, and Environmental Division (LH-SHRHA) in the Faculty of Engineering of the University of Porto–FEUP (Portugal), which contains two sediment pits, with a length of 3.4 m, a width of 1 m, and a depth of 0.4 m. The infrastructure can reproduce regular, irregular, and solitary waves up to 0.25 m in height, with a maximum water depth of 0.7 m, due to its upstream piston-type design. Co-directional currents are produced by two-intake pipelines, achieving a U_c of up to 0.16 m/s for a target water depth of $d = 0.4$ m.

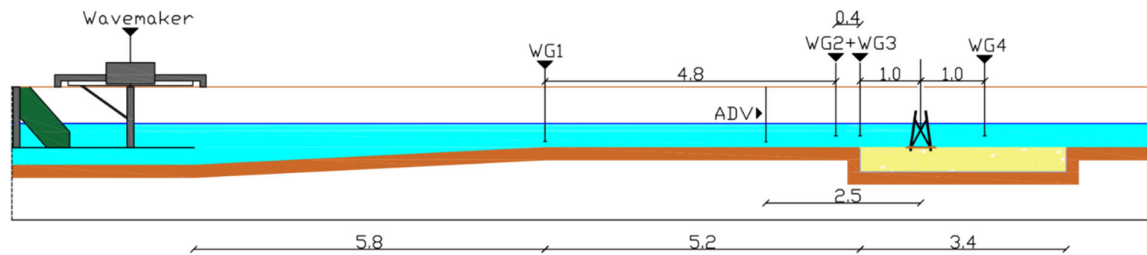


Figure 2. Partial flume's cross-section that represents the experimental setup, ADV, and wave gauge placement—dimensions in meters.

The experiments were conducted using a similar setup, geometric scale (1:50), and hydrodynamic conditions as in the research developed by [33], with incident waves propagating in the direction of the currents. Irregular waves were reproduced following JONSWAP spectrum with a peak enhancement factor $\gamma = 3.3$. The geometric scale was selected as the maximum feasible model size to fit the physical constraints of the wave-current flume while maximising the data resolution. The model follows a Froude (F_r) similitude to ensure the conservation of gravity effects, as gravity is the dominant driving force in free-surface flows and wave mechanics. However, when reproducing reduced-scale models, perfect similarity is unattainable due to inherent scale effects that arise from force ratios that are not identical between the model and the prototype, resulting in oversimplifications. One such case is the impossibility of simultaneously satisfying the Froude and Reynolds (Re) criteria, which relates to viscous-driven phenomena. According to ref. [35], scale effects resulting from the inaccurate scaling of the Re number can be mitigated for $10^3 < Re < 10^5$, a condition that was satisfied as the experimental setup's Re number was maintained within the range of $10^3 < Re < 10^4$.

Furthermore, one of the major limitations in scour testing is related to sediment scaling. While non-cohesive sediments were used to match the prototype's nature, the sediment size was not geometrically scaled to avoid introducing cohesive forces, which would be inconsistent with the prototype. Consequently, the dimensions of the ripples and the associated bed roughness are not geometrically scaled, which can contribute to potential deviations in sediment transport magnitude compared to prototype conditions. Minor scale effects related to the boundary layer and pile surface roughness are also acknowledged.

The free-surface elevation was recorded at 100 Hz by four resistive wave gauges positioned along the flume. One gauge was placed near the wavemaker, two gauges were positioned seaward of the model to measure the local wave conditions, and one final gauge was located on the leeward side to determine the effects of the model on wave transmission. Data from the gauges were used to estimate the U_m value using a MATLAB (v.R2022b) routine developed by [36].

Flow velocities were measured using an Acoustic Doppler Velocimeter (ADV; Vectrino+, Nortek AS, Rud, Norway) with a sampling rate of 100 Hz. The ADV was positioned 2.5 m upstream from the model at an elevation of 0.16 m ($0.4d$) above the bed, with the x -axis aligned with the current direction. The location was chosen to avoid signal interference from the bed ripple migration and to capture undisturbed flow conditions. Additional sensors were excluded from the immediate vicinity (side/rear) and inside the structure due to spatial constraints of both the flume and the model, to avoid blockage effects that could potentially induce significant flow disturbances and signal interference with the downstream wave gauge. The target U_c values were calibrated during preliminary tests conducted without waves.

The model of a generic four-leg jacket-type was constructed using stainless steel. The structure featured a 0.33 m-wide platform, 2.5 mm pile diameters, and diagonal

bracings of 1.5 mm—with no additional post piles and mud mats (Figure 3). The model was positioned 12 m from the wavemaker and 1 m from the leading edge of the first sediment box (Figure 2). The scour protection (Figure 4) was designed and constructed around the foundation with a square-shaped configuration with varying thickness. As suggested by [20], the armour layer thickness (t_s) was reinforced around the piles, indicated by the red squares in Figure 5, to $5D_{n50}$ (nominal median grain size) and $3D_{n50}$ in the adjacent areas, a range consistent with the scour depths reported by [31]. The protection's spatial extent covered 1.25 times the foundation's footprint (1.5 times including slopes), based on the scour patterns and findings reported by [21].

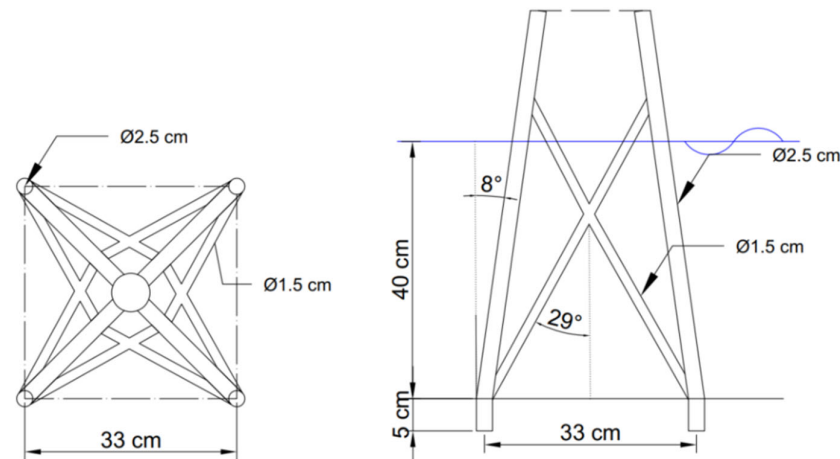


Figure 3. Jacket physical model scheme (geometric scale: 1:50).

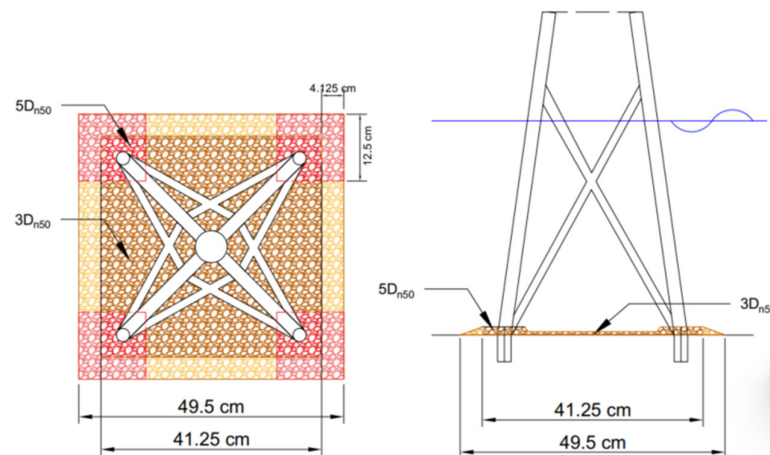


Figure 4. Scour protection model scheme—red/pink colours: $t_s = 5D_{n50}$; orange/brown colours: $t_s = 3D_{n50}$ (geometric scale: 1:50).

The armour layer material had a $D_{n50} = 3.696$ mm, a density of $\rho_s = 2666$ kg/m³, and a grading ratio $D_{85}/D_{15} = 3$, classifying it as a very wide grading material [37]. To visually track displacements, some stones around the piles were painted with different colours (Figure 5). A polypropylene geotextile with a surface density of 0.330 kg/m² was first deployed as a filter layer, with the same area as the armour layer. The sediment bed was composed of sand with a median diameter of $d_{50} = 0.215$ mm, a density of $\rho_s = 2590$ kg/m³, and a geometric standard deviation $\sigma_s = \sqrt{d_{84}/d_{16}} = 1.8$.



Figure 5. Scour protection for the four-leg jacket model.

One of the main objectives of this study was not only to investigate how scour develops for complex foundations, but also to address existing knowledge gaps concerning hybrid foundations. To evaluate the influence of a converter's oscillatory motion, the same OSWEC device used by [33] was adapted to fit the jacket foundation model. The converter corresponds to a simplified version of the FOSWEC (floating oscillating surge wave energy converter), originally designed, constructed, and tested by [38–40]. In this setup, the OSWEC model was attached to a cut-off section of the jacket via a square, flat, perforated platform, locking all the converter's body DOFs (Degrees-of-Freedom)—Figures 6 and 7. A tip clearance, i.e., vertical distance between the converter's bottom and the sediment bed, of 15 cm, was maintained (Figures 6 and 7). Instead of incorporating a PTO (Power Take-Off) system, a simplified spring-based mechanism was implemented to limit the flaps' pitch to a motion angle of $\pm 25^\circ$, consistent with the maximum motion of the FOSWEC device [38]. This simplification followed the rationale used by [33], which prioritises the impact evaluation of the device on flow amplification and scour enhancement over the assessment of the converter's power-harvesting capacity under the experimental conditions.

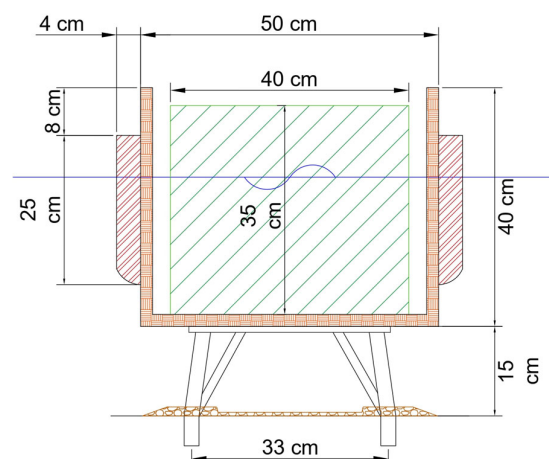


Figure 6. Hybrid jacket model scheme (geometric scale: 1:50).

In the tip clearance region, beneath the keel of the OSWEC and the sediment bed, the reference blockage ratio of $1/6$ proposed by [41] was maintained to ensure that the near-bed flow dynamics, which are critical driver of the scour process in this study, were affected by the OSWEC and by the distance of the device to the seabed, not by sidewall interference.



Figure 7. Hybrid jacket model.

Overall, the present study provides insights into scour around complex and hybrid jackets, emphasising the hydrodynamic interactions that govern scour protection performance. It is expected that the results will contribute to advancing the understanding of the complex process for both marine and offshore structures, with implications for the design optimisation of scour countermeasures.

2.2. Experimental Procedures, Measurements, and Test Conditions

The seabed bathymetry and scour were measured using a FARO® Focus (FARO Technologies, Lake Mary, FL, USA) laser scanner, capable of capturing 2 million points/second, with a 3D precision of 2 mm at 10 m and a 1 mm standard deviation at a range of 10–25 m. The scanner enables the measurement and generation of high-resolution 3D Digital Terrain Models (DTM), providing an accurate representation of erodible areas and their surroundings. Scans were conducted before and after each experimental test, as well as for each 1000-wave train. Since the scanner's precision is smaller than the armour layer's D_{n50} , even small unit displacements and spot deformations could be reliably detected.

DTM post-processing was carried out using Autodesk ReCap and CloudCompare, resulting in precise point clouds of the sediment bed, scour protection, and the foundation model profiles. The DTMs were subsequently analysed to determine scour depth and $S_{3D,measured}$ values, through a MATLAB (v.R2022b) routine developed to adapt the overlapping-circle method to four-leg jackets and square-shaped scour protections. The methodology established by [34] was initially developed for monopiles and circular scour protection, utilising radial symmetry to define the mesh. While effective for circular cross-sections, this approach was not prepared to address other complex foundations and different protection geometries. In this study, we introduce a novel adaptation of this method, generalising the mesh-grid generation process to map onto complex, non-circular geometries. This approach allows the method to be applied to a wide range of marine and offshore structures, independent of their geometric complexity. To the author's knowledge, this was the first successful application of this mesh-based approach to a complex scour protection-foundation setup. Complementary visual observations and photographic records were systematically collected to support and validate the results obtained and to compare the observed material displacements to the measured damage.

The hydrodynamic conditions used in this study (Table 1) were based on those of ref. [33], allowing for a comparison of scour effects on protection for offshore foundations with different geometries. These conditions covered different ranges of U_{cw} and KC . Each test was conducted for up to 3000 waves, unless premature failure of the scour protection occurred. Three types of hydrodynamic conditions were used for the jacket (J) and hybrid jacket (JH): irregular waves combined with co-directional currents (WC),

irregular waves-only (WI), and regular waves-only (WR). For the selected hydrodynamics and scour protection configurations, different responses of the scour protection were anticipated, mainly ranging from stable to dynamic behaviour, and possible failure for the hybrid jacket.

Table 1. Physical model hydrodynamic conditions (geometric scale: 1:50).

Test	Number of Waves	D_{jacket} [m]	d [m]	H_s [m]	T_p [s]	U_m [m/s]	U_c [m/s]	U_{cw}	$S_{3D,predicted}$	KC
J_WC_7	3000	0.025	0.4	0.07	1.414	0.080	0.155	0.66	0.08	4.52
J_WC_11				0.11	1.697	0.143		0.52	0.63	9.71
J_WC_15.5				0.155	1.980	0.183		0.21	1.79	14.49
J_WI_14				0.14	2.263	0.208	-	0.00	3.43	18.83
J_WR_14				0.14 (Regular)						
JH_WC_7	3000	0.025	0.4	0.07	1.414	0.080	0.155	0.66	0.08	4.52
JH_WC_11				0.11	1.697	0.143		0.52	0.63	9.71
JH_WC_15.5				0.155	1.980	0.183		0.21	1.79	14.49
JH_WI_14				0.14	2.263	0.208	-	0.00	3.43	18.83
JH_WR_14				0.14 (Regular)						

2.3. Method of Analysis

The analysis of the experimental results combines high-resolution spatial damage quantification with novel methodologies and comparisons to existing predictive formulas, as well as the assessment of alternative performance-aligned scour metrics. As previously mentioned, the damage quantification utilises an adaptation of the overlapping-circle method [34]. The method was developed to characterise damage in circular rubble mound scour protections for monopiles. It was demonstrated that the resulting S_{3D} was highly sensitive to the selected grid ratio ($\eta_{S3D,grid}$).

The effectiveness of the technique has been recently applied to both a monopile and a hybrid monopile by [33], concluding that the analysis of the maximum damage ($S_{3D,max}$) across different grid ratios was effective when compared to other methods [5,42]. The results obtained by [33] also confirmed that the sensitivity of the grid ratio by performing a statistical evaluation of the standard deviation and the 95th percentile (P_{95}) of the damage number, concluding that the optimal value converges to a grid ratio interval of 1/6 to 1/4, aligned with the findings reported by [34].

Despite the method's flexibility in accommodating complex scour protection geometries and foundations, the methodology was shifted from the original radial discretisation centred on the monopile to a linear vertex-initiated grid generation. This approach builds the mesh row by row from the protection's upper boundary, ensuring spatially homogeneous overlapping distances across the entire domain. While this topology minimises data noise and complies with the overlapping distance defined in the inputs, it presents challenges related to discretisation near the piles when using large sub-areas. By reducing the sub-areas (A_{sub}) of the circles, a mesh refinement is generated locally, thereby increasing resolution and accuracy in the critical zones immediately surrounding the piles.

In addition, alternative performance-aligned scour metrics, S/t_s (scour depth relative to the scour protection thickness) and S_{3D}/n_s (damage number relative to the number of rock stone layers), will also be evaluated. The S/t_s and S_{3D}/n_s ratios provide a more accurate and straightforward indicator of scour protection performance in complex wave-current hydrodynamics [33]. By shifting the relative reference from the foundation diameter to the protection thickness, these metrics provide a more accurate representation of the

riprap state and the performance of the scour protection. Specifically, they offer a more reliable basis for future design approaches by moving beyond the S/D and S_{3D} thresholds of 1.0, which are often limited in scope.

Given the inclusion of a WEC as part of the hybrid jacket, a hydrodynamic analysis could also provide valuable information. As the focus of this study was not on the WEC's performance or efficiency, but instead on the influence of the device on its surroundings, particularly its potential to modify flow patterns and therefore the potential to enhance scour, only two simple metrics, the wave transmission coefficient (K_t) and the wave reduction coefficient (K_{Red}), were measured. These coefficients will provide insight into the modifications in the flow field induced by the presence of the WEC, offering an understanding of the coupling effects of integrating a WEC into an offshore foundation.

3. Results

3.1. Damage Number (S_{3D})

For all the tests, the overlapping-circle technique was applied using a $A_{sub} = 4D_{n50}^2$ and an overlapping distance of 50%, as described by [34], allowing for an objective quantification of the scour protection damage under each test condition. Table 2 summarises all the measured conditions. The U_{cw} values distinguish the wave-dominated tests ($U_{cw} < 0.44$) from the current-dominated tests ($U_{cw} > 0.44$). The novel yielded high-resolution representations of the scour patterns, showing high accuracy in measuring S_{3D} values and representing the damage's spatial distribution (see Appendix A). As expected, S_{3D} generally correlates highly with the intensity of the hydrodynamic load. For low-energy conditions, the $S_{3D,max}$ values were lower and increased with higher wave heights and periods. Also, when comparing the results of the wave-only tests (J_WI vs. J_WR and JH_WI vs. JH_WR), the S_{3D} values were slightly higher when using regular waves, aligned with a study performed by [43] concerning a rubble-mound structure, which attributed these differences to the fact that the root-mean-square wave height (H_{rms}) for irregular waves tends to be smaller than the wave height for regular waves.

Table 2. Experimental measured conditions for scour protection tests—model values.

Test	N	H_{m0} [m]	T_p [s]	U_m [m/s]	U_c [m/s]	U_{cw}	$S_{3D,max}$	$S_{3D,predicted}$	KC
J_WC_7_1000	1000	0.069	1.471	0.081	0.156	0.66	1.61	0.07	4.79
J_WC_7_2000	1000	0.068	1.471	0.080	0.157	0.66	1.76	0.08	4.72
J_WC_7_3000	1000	0.069	1.471	0.081	0.157	0.66	1.72	0.09	4.79
J_WC_11_1000	1000	0.100	1.695	0.130	0.158	0.55	1.67	0.36	8.83
J_WC_11_2000	1000	0.103	1.613	0.130	0.156	0.55	1.80	0.39	8.39
J_WC_11_3000	1000	0.106	1.667	0.137	0.157	0.53	1.98	0.53	9.11
J_WC_15.5_1000	1000	0.145	1.887	0.200	0.051	0.20	3.27	1.62	15.09
J_WC_15.5_2000	1000	0.148	1.887	0.204	0.048	0.19	4.62	2.04	15.41
J_WC_15.5_3000	1000	0.148	1.887	0.204	0.048	0.19	4.71	2.25	15.41
J_WI_14_1000	1000	0.136	2.128	0.192			3.85	1.83	16.32
J_WI_14_2000	1000	0.135	2.174	0.190	-	0.00	3.67	2.19	16.48
J_WI_14_3000	1000	0.137	2.083	0.196			3.96	2.43	16.30
J_WR_14_1000	1000	0.138	2.222	0.203			2.83	2.35	18.07
J_WR_14_2000	1000	0.138	2.222	0.203	-	0.00	3.72	2.78	18.07
J_WR_14_3000	1000	0.134	2.222	0.197			4.90	2.81	17.54
JH_WC_7_1000	1000	0.068	1.471	0.080	0.155	0.66	3.02	0.06	4.72
JH_WC_7_2000	1000	0.069	1.471	0.081	0.154	0.65	3.01	0.09	4.79
JH_WC_7_3000	1000	0.071	1.471	0.084	0.155	0.65	3.65	0.10	4.93
JH_WC_11_1000	1000	0.111	1.695	0.145	0.156	0.52	10.40	0.50	9.80
JH_WC_15.5_1000	1000	0.154	1.961	0.216	0.049	0.18	19.10	2.21	16.95
JH_WI_14_1000	1000	0.142	2.273	0.211	-	0.00	16.00	2.77	19.17
JH_WR_14_1000	1000	0.147	2.273	0.218	-	0.00	16.80	3.05	19.85

Under all tested hydrodynamic conditions, the scour protections associated with the jacket test configurations (J_WC, J_WI, and J_WR) demonstrated consistently lower damage rates when compared to those in hybrid jackets (JH_WC, JH_WI, and JH_WR), as evidenced in Figures A1–A22 and Table 2. In alignment with the findings of ref. [33], the hybrid configuration exhibited pronounced scour deformations, particularly under moderate to high hydrodynamic regimes. The damage amplification was both quantitatively measured and visually confirmed, correlating high S_{3D} values with severe sediment displacement, extensive washout of the armour layer material, and substantial sinking of the seabed beneath the filter layer (Figure 8).

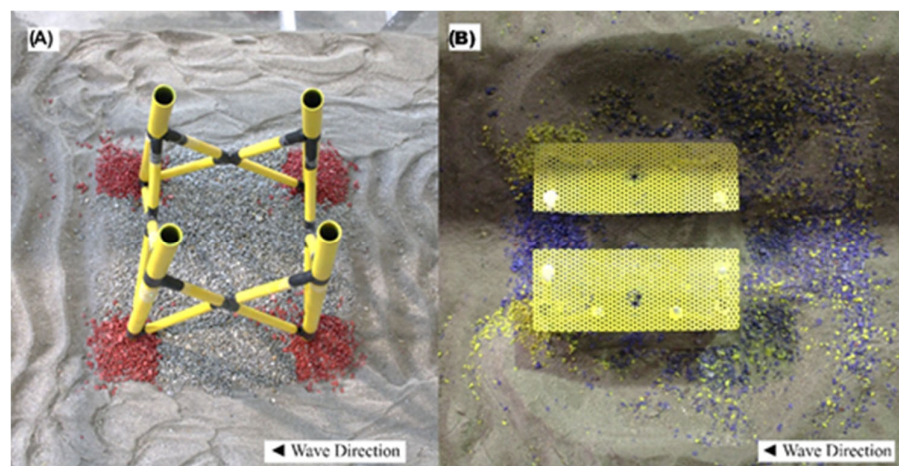


Figure 8. Comparison of scour protection damage under wave loading: (A) J_WR_14_1000 (Jacket) and (B) JH_WR_14_1000 (Hybrid Jacket). The hybrid jacket visualisation represents the final state following extensive armour layer deformation, after only 1000 waves.

The damage number in the hybrid jackets was increased by factors ranging from 1.71 to 6.23 (Table 3), suggesting that the hydrodynamic interaction induced by the WEC exerts a significantly more destabilising influence on the scour protection integrity than the geometric complexity of the jacket structure alone.

Table 3. Damage amplification comparison between jacket and hybrid jacket tests.

Test	N	$S_{3D,hybrid}/S_{3D,jacket}$
J_WC_7 vs. JH_WC_7	1000	1.88
	2000	1.71
	3000	2.12
J_WC_11 vs. JH_WC_11	1000	6.23
	2000	-
	3000	-
J_WC_15.5 vs. JH_WC_15.5	1000	5.84
	2000	-
	3000	-
J_WI_14 vs. JH_WI_14	1000	4.16
	2000	-
	3000	-
J_WR_14 vs. JH_WR_14	1000	5.94
	2000	-
	3000	-

For most of the hybrid jacket tests, failure occurred within the first 1000 waves, with a damage number significantly above the $S_{3D} > 1.0$ failure threshold. The only hybrid test that provided scour protection support and successfully endured the flow-enhanced patterns for the duration of all 3000 waves was the JH_WC_7. In this test, the initial visual inspection suggested a static behaviour (Figures A16–A18), as no intense movement of the armour layer units was observed. However, the measured damage number (Table 2) indicated a value significantly above the $S_{3D} > 0.25$ static threshold defined by [5], due to edge scour occurring on the leeward side of the protection. Therefore, the protection was visually deemed to be on the edge between the static and dynamic behaviour.

Although sediment-flow-structure interactions in jackets have been well reported in the literature, the results obtained for the hybrid jackets confirm that the OSWEC body and the oscillatory movement of its paddles are responsible for enhancing the flow patterns that contribute to scour dynamics. The oscillatory movement of the front paddles appears to enhance downward pressures, downflow, and horseshoe vortices. In contrast, the movement of the downstream paddle seems to strengthen the intensity of the lee-wake and counter-rotating vortices. Moreover, due to the dimensions of the WEC, the approaching flow conditions increase the streamline contractions around and beneath the device.

As for the jacket foundation, the scour protection retained its effectiveness throughout the entire experimental test (all 3000 waves), demonstrating an apparent static behaviour for the first two tested conditions and a dynamic behaviour for the remaining conditions. However, for the J_WC_15.5 and J_WR_14 tests, the protection almost reached failure in the back-pile region (see Appendix A Figures A9 and A15). For the jacket test set, the measured damage number failed to be within the static and failure thresholds defined by [5] when classifying the scour protections according to the level of deformation and visual classification.

The highest $S_{3D,max}$ values in this study were associated with increased wave heights and longer wave periods, as observed by [23]. When analysing the damage distribution near the pile reinforced region in jacket-only configurations, using parameters such as the mean damage, the 90th or 95th percentile, the results indicated that the front pile region was more affected by scour when subjected to waves with shorter peak periods. For larger T_p values, the same parameters pointed out that the most affected regions shifted to the rear-pile area (Table 4), an observation also reported by [23], except for the J_WI_14 test, where damage had a distribution very similar in value but with a slight edge to one of the front piles.

Table 4. Dependency of the most affected area on the peak period (T_p).

Test	T_p [s]	Most Affected Region	
		Front Pile	Rear Pile
J_WC_7	1.471	x	
J_WC_11	[1.613–1.695]	x	
J_WC_15.5	1.887		x
J_WI_14	[2.083–2.174]	x	
J_WR_14	2.222		x
JH_WC_7	1.471	x	
JH_WC_11	1.695	x	
JH_WC_15.5	1.961	x	
JH_WI_14	2.273	x	
JH_WR_14	2.273	x	

The observed shift in the most damaged zone from the front to the rear-pile region with increasing wave height and peak period could be attributed to a transition in the most dominant scour mechanism. Under lower H_s and T_p conditions, damage is primarily driven by local horseshoe vortices formed at the front piles, while rear piles benefit from a sheltering effect provided by the upstream structural elements. Conversely, under more energetic conditions, the interaction between the flow and the jacket's structural elements intensifies. This results, on the rear pile region, in stronger wake vortices shedding, more pronounced horseshoe vortices, and a significant increase in streamline contractions between the legs and around the edge of the protection. The consequent flow acceleration and amplification of turbulence and shear stresses acting in the wake region of the scour protection explain the higher damage rate observed in the rear section of the jacket foundation.

In contrast, the hybrid jackets consistently exhibited massive damage rates at the front piles across all test conditions. Test JH_WC_15.5 (Figure A20) revealed extensive damage to both the front and rear piles, although the front was affected more significantly. These findings suggest that the integration of the WEC fundamentally alters the scour distribution pattern, may diminish the influence of the peak period, and induce intensified scour rates at the frontal areas.

A distinct disparity was observed between the $S_{3D,max}$ and the $S_{3D,predicted}$, Table 2, using the formula developed by [5]. Overall, predictive values underestimate scour for both the jacket and the hybrid jacket. For the hybrid jacket foundations, the difference was even more noticeable. The underestimation could imply that the formula is not well-suited for complex geometry foundations, that it does not account for nonlinear elements related to intricate hydrodynamics in hybrid systems, or that the measuring sub-areas approach between the two methods is inherently different. Moreover, the differences between the measured and predicted values also illustrate the fundamental approach distinctions between the methodologies developed by [5,34]. The former employs fixed sub-areas equivalent to the monopile cross-section, averaging the scour depth over larger regions and neglecting the protection thickness, and is thus only applicable to circular geometries so far. In contrast, the latter employs mobile, overlapping sub-areas of predefined size, allowing for higher-resolution damage assessment.

3.2. Overlapping Grid Ratio

The damage assessment methodology originally established by [34] was predicated on the radial symmetry of monopile foundations and circular scour protections. While effective for circular cross-sections, this radial approach lacks the versatility required for the complex, non-circular geometries utilised in this study (e.g., multi-pile foundation and squared protection layout). To overcome this geometric constraint, a novel adaptation of the algorithm was developed, transitioning from a structure-centred radial grid to a linear, vertex-initiated topology (Figure 9). This approach generates the mesh row by row from the protection's boundary, ensuring spatially homogeneous overlapping distances across the entire domain. Furthermore, to resolve discretisation challenges near the piles' interface, local mesh refinement can be applied by reducing the sampling sub-areas, thereby maximising resolution and accuracy in these critical zones. As previously mentioned, to the authors' knowledge, this constitutes the first successful generalisation of the overlapping-circle method to complex scour protection-foundation combinations.

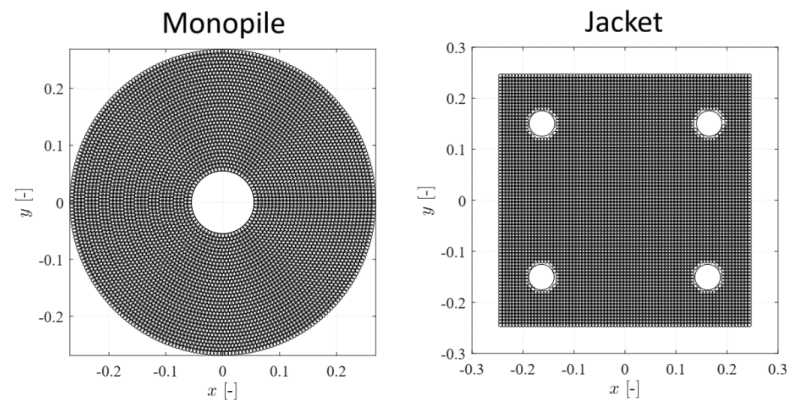


Figure 9. Overlapping-circle method sub-area arrangement for different structures ($A_{sub} = 4D_{n50}^2$).

It was demonstrated by [34] that the computed damage number was susceptible to the grid ratio. Therefore, an analysis of the $S_{3D,max}$ variation across different $\eta_{S3D,grid}$ was conducted. Additionally, since the maximum damage number corresponds to the value at the deepest point within the scour protection, a statistical assessment of the standard deviation and the 95th percentile of the damage number was performed to assess potential convergence behaviour.

The selected grid ratios encompassed a wide range of A_{sub} values, Figure 10, including the jacket pile cross section, A_{pile_jacket} , $4D_{n50}^2$ as in ref. [6], D_{n50}^2 as a metric for possible detection of spot deformations, and several others that represent multiple arrangements of armour layer units ($nD_{n50} \times nD_{n50}$ or $nD_{n50} \times mD_{n50}$).

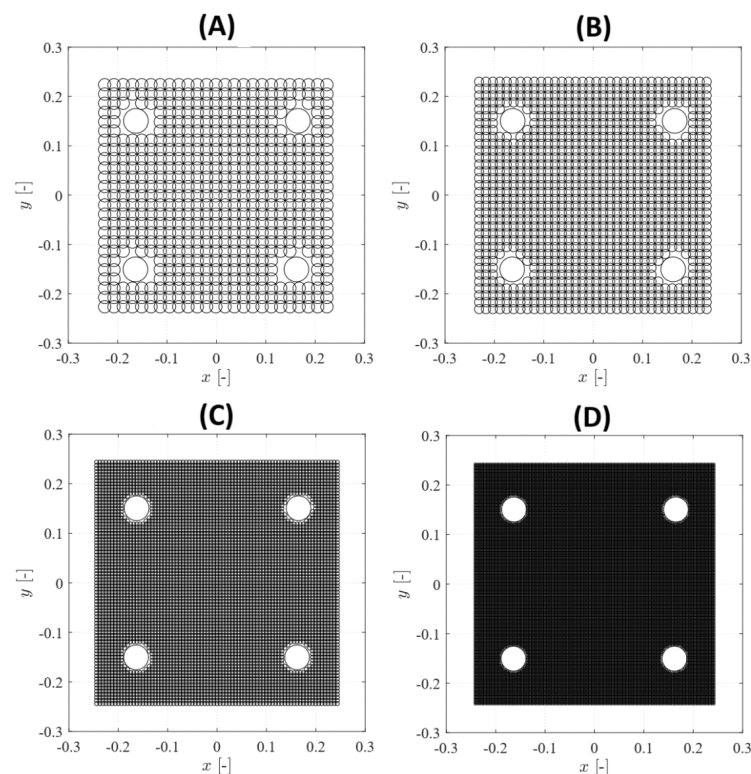


Figure 10. Overlapping-circle sub-area arrangement for different $\eta_{S3D,grid}$: (A) $\eta_{S3D,grid} = 2.78 \times 10^{-2}$, $A_{sub} = A_{pile_jacket}$; (B) $\eta_{S3D,grid} = 1/20$, $A_{sub} = 20D_{n50}^2$; (C) $\eta_{S3D,grid} = 1/4$, $A_{sub} = 4D_{n50}^2$; (D) $\eta_{S3D,grid} = 1$, $A_{sub} = D_{n50}^2$.

Modifying the grid ratio affects the number of elements analysed, resulting in significant variations in $S_{3D,max}$, and considerable variations in the accuracy of measurements near

the piles. Higher grid ratios, corresponding to smaller A_{sub} and more elements analysed, produced scour representations that closely match the detailed topography obtained from DTMs. In contrast, lower grid ratios, which are associated with larger A_{sub} and fewer elements analysed, can be less accurate and exhibit difficulties in properly representing overlapping elements near the corners and around the piles. Figure 11 illustrates this effect for the J_WI_14_3000 case, where a considerable variation in the damage number was observed for different ratios: for $A_{sub} = A_{pile_jacket}$, the larger sub-area and least amount of elements analysed, a $S_{3D,max} = 3.21$ was obtained, whereas for $A_{sub} = D_{n50}^2$, the smaller sub-area and highest amount of analysed elements, a $S_{3D,max} = 5.14$ was registered, representing an increase of almost 64%—a possible result of localized, possibly a spot deformation with negligible filter exposure.

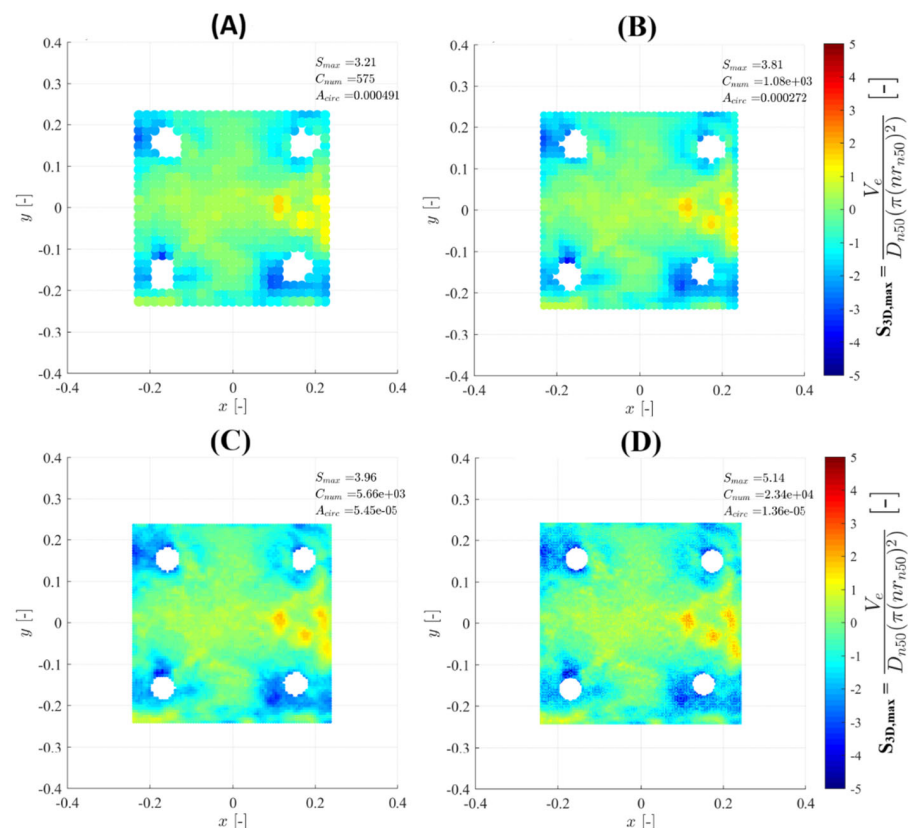


Figure 11. Influence of $\eta_{S3D,grid}$ on $S_{3D,max}$ value (J_WI_14_3000): (A) $\eta_{S3D,grid} = 2.78 \times 10^{-2}$, $A_{sub} = A_{pile_jacket}$, $S_{3D,max} = 3.49$; (B) $\eta_{S3D,grid} = 1/20$, $A_{sub} = 20D_{n50}^2$, $S_{3D,max} = 3.40$; (C) $\eta_{S3D,grid} = 1/4$, $A_{sub} = 4D_{n50}^2$, $S_{3D,max} = 3.96$; (D) $\eta_{S3D,grid} = 1$, $A_{sub} = D_{n50}^2$, $S_{3D,max} = 5.14$.

Figure 12 (jacket) and Figure 13 (hybrid jacket) plot the $S_{3D,max}$ vs. $\eta_{S3D,grid}$ results present in Table A1 (jacket) and Table A2 (hybrid jacket). Both plots reveal a dependence and positive correlation between the two variables, which aligns with the findings reported by [34]. This demonstrates that the grid ratio needs to be carefully selected, as it can provide a wide range of outcomes, which may result in different interpretations of scour protection behaviour. The results support the need to develop a universal failure criterion for assessing scour protection performance.

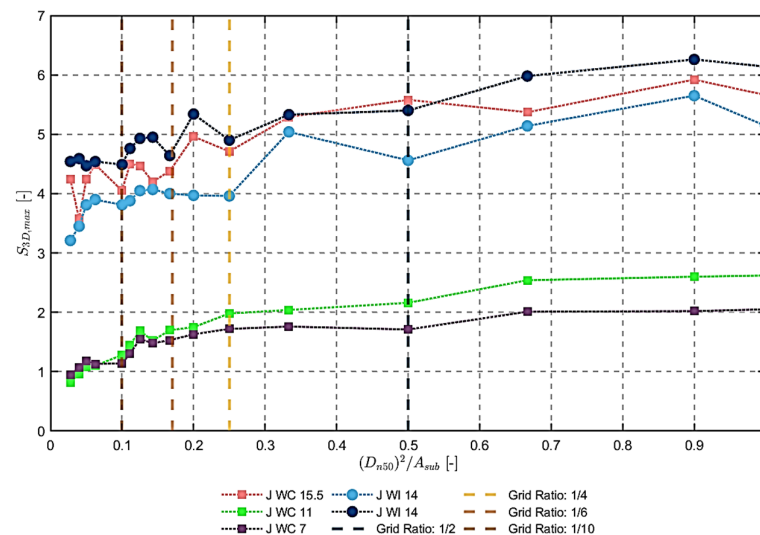


Figure 12. Variation in $S_{3D,max}$ with $\eta_{S3D,grid}$ —Jacket Tests.

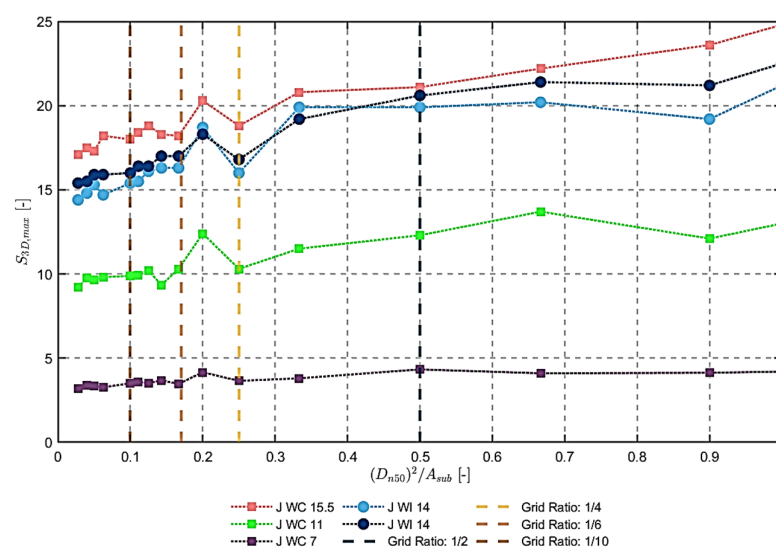


Figure 13. Variation in $S_{3D,max}$ with $\eta_{S3D,grid}$ —Hybrid Jacket Tests.

The $S_{3D,max}$ growth for the jacket foundation in Figure 12 resembles a logarithmic trend from $\eta_{S3D,grid} = 2.78 \times 10^{-2}$ ($A_{sub} = A_{pile_jacket}$) to $\eta_{S3D,grid} = 1/4$ ($A_{sub} = 4D_{n50}^2$). For the highest wave conditions tested, the damage number shows an erratic variation in this interval. From $\eta_{S3D,grid} = 1/4$ to $\eta_{S3D,grid} = 1$ ($A_{sub} = D_{n50}^2$), in general, $S_{3D,max}$ follows a linear trend. The hybrid jacket (Figure 13) exhibits a linear increase in $S_{3D,max}$, primarily due to the extreme damage suffered by the scour protection and seabed throughout almost all grid ratios and test conditions. For both foundations, a localized spike is seen for $\eta_{S3D,grid} = 1/5$ ($A_{sub} = 5D_{n50}^2$) in most of the tests.

Based on the results, the most suitable range of grid ratios and sub-areas values to accurately determine the protection's S_{3D} in foundations and protections with a complex geometry, seems to be located within the $\eta_{S3D,grid} = 1/8$ ($A_{sub} = 8D_{n50}^2$) to $\eta_{S3D,grid} = 1/4$ ($A_{sub} = 4D_{n50}^2$) range, except $\eta_{S3D,grid} = 1/5$ ($A_{sub} = 5D_{n50}^2$). The ideal range for monopiles and common scour protection geometries was determined by [33] to be $\eta_{S3D,grid} = 1/6$ ($A_{sub} = 6D_{n50}^2$) to $\eta_{S3D,grid} = 1/4$ ($A_{sub} = 4D_{n50}^2$), with the same $\eta_{S3D,grid} = 1/5$ exception. As a result, both findings align with previous research performed by [34], supporting the adaptability of the overlapping method to various foundations and scour protection geometries. Albeit, since low grid ratios, i.e., high A_{sub} values, exhibit difficulties in

properly representing and overlapping elements near the corners and around the piles in complex foundations and squared protections, $\eta_{S3D,grid} = 1/4$ ($A_{sub} = 4D_{n50}^2$) seems to be the most suitable grid ratio-sub-area selection to be applied independently of the foundation and scour protection's configuration. Hence, it implies that the failure criterion set by [6] may still be, in fact, the most reasonable cut-off threshold to identify failure correctly.

The standard deviation (Figure 14) and the 95th percentile (Figure 15) of all $S_{3D,sub}$ values were plotted against the jacket tests to confirm the convergence behaviour across all grid ratios analysed, since $S_{3D,max}$ appears to be particularly sensitive to small fluctuations in $\eta_{S3D,grid}$. Up to $\eta_{S3D,grid} = 1/4$, both metrics show a slight logarithmic trend, followed by a nearly linear trend beyond this point. Predominantly, there is marginal variation for grid ratios above $1/6$, and even above $1/10$ in 4 out of the five conditions tested for the 95th percentile (Figure 15). The evolution of these statistical metrics as a function of the grid ratio shows considerably less variability than $S_{3D,max}$, providing a clear indicator of damage convergence. Both these metrics are beneficial since they are less affected by small fluctuations in the scour pattern, such as spot deformations or the displacement of a single armour layer unit. As a result, incorporating the standard deviation and 95th percentile assessment ensures a more robust damage evaluation that does not rely solely on the damage number, while confirming that convergence is reached for the selected grid ratio and the respective sub-area. Overall, the overlapping-circle method has a negligible impact on the convergence of statistical parameters.

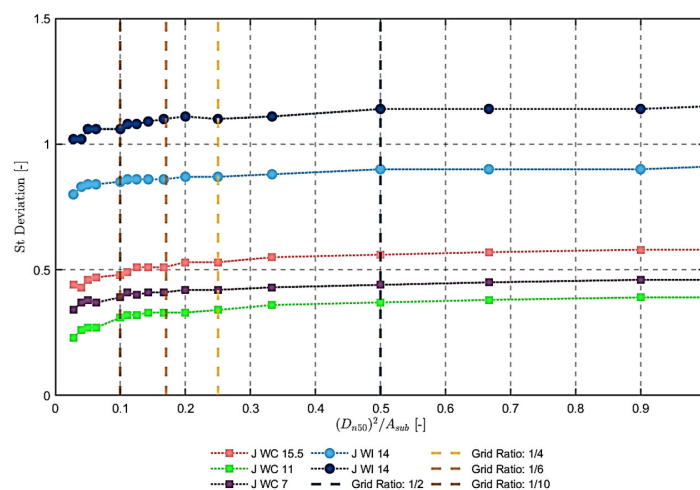


Figure 14. Variation in the standard deviation of $S_{3D,sub}$ with $\eta_{S3D,grid}$ —Jacket.

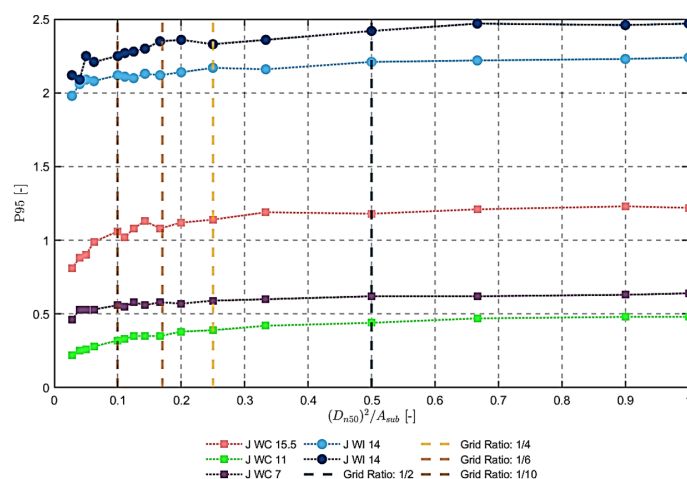


Figure 15. Variation in the 95% Percentile (P_{95}) of $S_{3D,sub}$ with $\eta_{S3D,grid}$ —Jacket.

3.3. S_{3D}/n_s and S/t_s Analysis

The damage number was defined by [5] as the number of protection layers lost to scour, normalised by D_{n50} , with static and failure limits of $S_{3D} > 0.25$ and $S_{3D} > 1.0$, respectively. Consequently, observing a $S_{3D} > 1.0$ for a model thickness of $t_s = 5D_{n50}$ around the piles, or $t_s = 3D_{n50}$ in the remaining area, may be overly conservative and not accurately reflect failure, since it only represents a loss of a layer. On the contrary, the method developed by [34], which applies the ref. [6] failure criterion, suggests that filter exposure and failure only occur under the specific $S_{3D} \times D_{n50} \geq t_s$ condition. In this context, ref. [33] demonstrated that a comparison between S_{3D} with t_s , as a function of D_{n50} , provides additional insight into the actual state of the protection. Without disregarding the necessity to account for a certain degree of uncertainty, it is recommended to establish the failure limit ($S_{3D, failure}$) as a range around $S_{3D, failure} = n_s$ for $t_s = n_s \times D_{n50}$.

By adopting this perspective, comparing $S_{3D, max}$ values against a failure threshold of $S_{3D} = 5.0$ (Table 5) facilitates a more precise assessment of the protection's behaviour, particularly when applying the overlapping method, and a better understanding of the physical meaning behind the damage number. Although it was suggested by [33] to set the static limit at 0.25, in line with ref. [5], further examination of the results, mainly for the J_WC_7 and J_WC_11 cases (test categorised as static), revealed that $S_{3D, measured}$ values exceeded this threshold.

Table 5. $S_{3D, max}$ comparison with static and failure threshold proposed based on the protection's thickness.

Test	$S_{3D, max}$	Static Threshold	Failure Threshold
J_WC_7_1000	1.61	$S_{3D} = 0.25$ ([5])	$S_{3D} = 5.0$ (based on n_s —[33])
J_WC_7_2000	1.76		
J_WC_7_3000	1.72		
J_WC_11_1000	1.67		
J_WC_11_2000	1.80		
J_WC_11_3000	1.98		
J_WC_15.5_1000	3.27		
J_WC_15.5_2000	4.62		
J_WC_15.5_3000	4.71		
J_WI_14_1000	3.85		
J_WI_14_2000	3.67		
J_WI_14_3000	3.96		
J_WR_14_1000	2.83		
J_WR_14_2000	3.72		
J_WR_14_3000	4.90		
JH_WC_7_1000	3.02		
JH_WC_7_2000	3.01		
JH_WC_7_3000	3.65		
JH_WC_11_1000	10.40		
JH_WC_15.5_1000	19.10		
JH_WI_14_1000	16.00		
JH_WR_14_1000	16.80		

This discrepancy highlights the necessity for both static and failure limits to be defined relative to the protection thickness, not solely the last one. The static limit $S_{3D} = 0.25$ was appropriate for circular protections with $t_s = 2.5D_{n50}$ used by both [5,33]. However, for complex structures and scour configurations/thicknesses, a fixed threshold has proven incompatible. This reinforces the assessment that both boundaries for classifying scour

protections should be established as a certain percentage of t_s value and/or defined by a range, rather than a single fixed value.

The damage increase ratio ($\Delta S_{3D}/n_s$), introduced by [8], emerged as an alternative to the drawbacks of the fixed sub-areas approach by [5]. Despite being effective in describing the pace at which damage evolves, ref. [33] demonstrated that it fails to reliably indicate the proximity of protection to failure and observed overlapping ranges across the three different behavioural categories. Similarly, for riprap protections, the conventional S/D ratio has limited relevance, as it poorly reflects the deformation status or the loss of armour layers.

As a result, S/t_s and S_{3D}/n_s ratios suggested by [33] are employed in this research, which provides a more robust physical correspondence of the protection's overall damage state. The following threshold ratios were defined for the following:

- Failure: $S_{3D}/n_s > 1$ or $S/t_s > 1$;
- Dynamic Protection: $0.25 < S_{3D}/n_s$ or $S/t_s < 1$;
- Static Protection: $0 < S_{3D}/n_s$ or $S/t_s < 0.25$;
- Recovery (Sediment Accretion): $S_{3D}/n_s < 0$ or $S/t_s < 0$;

The proposed limits for the two ratios were applied to rate the scour protection. Failures detected visually or by the overlapping-circle method corresponded to S_{3D}/n_s or $S/t_s > 1.0$, while dynamic protections remained below these limits (Table 6). However, for the static J_WC_7 and J_WC_11 tests, S_{3D}/n_s or $S/t_s < 0.25$ conditions were not satisfied, with most values ranging approximately around 1/3. These results imply that, despite both ratios being reliable in capturing dynamic or failure behaviour, the static limit should be reevaluated or adjusted to accommodate complex structural and different protection configurations.

Table 6. Scour depth (S), S_{3D}/n_s , and S/t_s comparison.

Test	S [mm]	S/t_s or S_{3D}/n_s	Static Threshold	Failure Threshold
J_WC_7_1000	5.95	0.32	0.25	1.0
J_WC_7_2000	6.50	0.35		
J_WC_7_3000	6.36	0.34		
J_WC_11_1000	6.17	0.33		
J_WC_11_2000	6.65	0.36		
J_WC_11_3000	7.32	0.40		
J_WC_15.5_1000	12.09	0.65		
J_WC_15.5_2000	17.08	0.92		
J_WC_15.5_3000	17.41	0.94		
J_WI_14_1000	14.23	0.77		
J_WI_14_2000	13.56	0.73		
J_WI_14_3000	14.64	0.79		
J_WR_14_1000	10.46	0.57		
J_WR_14_2000	13.75	0.74		
J_WR_14_3000	18.11	0.98		
JH_WC_7_1000	11.16	0.60		
JH_WC_7_2000	11.12	0.60		
JH_WC_7_3000	13.49	0.73		
JH_WC_11_1000	38.44	2.08		
JH_WC_15.5_1000	70.59	3.82		
JH_WI_14_1000	59.14	3.20		
JH_WR_14_1000	62.09	3.36		

Ultimately, the overlapping approach emerges as highly effective for visualising and measuring scour, offering a consistent tool for damage evaluation and/or identification. Moreover, the ratio-based indicators, such as S_{3D}/n_s , and S/t_s , show promise for developing adaptive design frameworks, thereby enhancing the reliability of scour protections in complex hydrodynamic environments.

3.4. U_{cw} and KC Effects

The analysis of damage evolution in relation to U_{cw} ratio reveals that S_{3D} values tend to increase as U_{cw} decreases (Table 2 and Figure 16), contrary to the findings reported by [15]. The results, however, are not regarded as conflicting. Instead, they offer additional proof of the intricacy of the wave-current regime, emphasising that the analysis cannot be made without considering the impact and importance of the KC number. In fact, the tendency majorly reflects the hydrodynamic conditions imposed during testing: higher U_{cw} tests were characterised by reduced wave heights and elevated current velocities, whereas lower U_{cw} values were performed using more energetic wave conditions—namely, higher wave heights with lower influence of current.

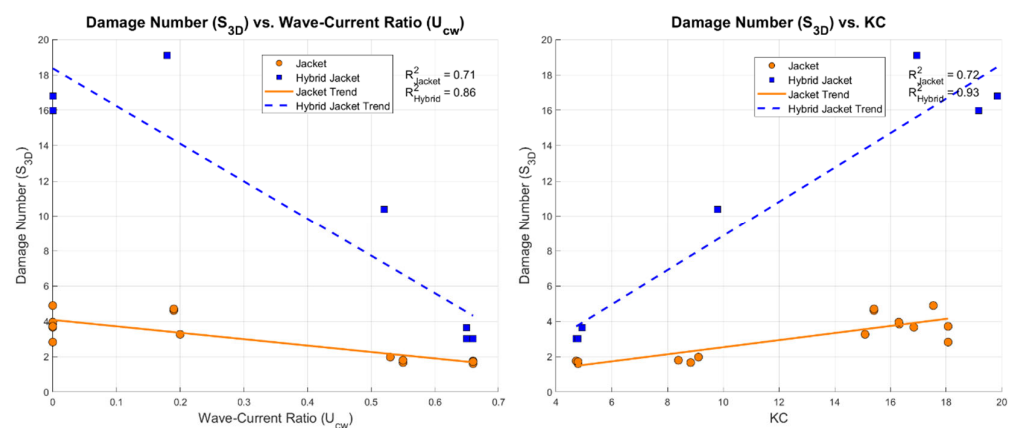


Figure 16. Damage number comparison with U_{cw} (right) and KC number (left).

As noted by [23], increased wave energy significantly amplifies scour rates. Further examination of tests with comparable KC numbers (J_WC_15.5, J_WI_14, and J_WR_14) indicates that the J_WC_15.5_3000 test ($KC = 15.41$, $U_{cw} = 0.19$, $S_{3D,max} = 4.71$) exhibited damage numbers that were slightly larger than or similar to those recorded in the J_WI_14_3000 ($KC = 16.30$, $U_{cw} = 0$, $S_{3D,max} = 3.96$) and J_WR_14_3000 tests ($KC = 17.54$, $U_{cw} = 0$, $S_{3D,max} = 4.90$), respectively. This small sample aligns with findings reported by [15,44], for jacket and monopile foundations, respectively, that a slight superimposition of a current load can increase scour depths.

Overall, the results presented in Table 2 and Figure 16, consistently indicate that damage increases with increasing KC values, regardless of the prevailing hydrodynamic regime, as it is directly related to the amplification of shear stress and vortex shedding around the foundation, the primary cause of scour. When comparing the jacket-only configurations with the hybrid jackets, the influence of a lower U_{cw} ratio was found to be even more pronounced for the hybrid structures. Deformation is highly influenced by intensified oscillatory flow patterns and by enhanced shear stresses (captured by KC number). The intensified damage rates associated with high KC and reduced U_{cw} values can be attributed to the distinctive hydrodynamic interactions induced by the oscillatory motion of the OSWEC paddle. In highly energetic, wave-dominated regimes, this motion generates significant variations in local flow velocities and pore pressures, thereby enhancing bed shear stress, turbulence, and upward/downward pressure cycles, as well as flow acceleration in the

vicinity of the structure. These dynamic interactions serve as an additional scour-driving mechanism, substantially increasing sediment mobilisation compared to conventional jacket foundations under similar conditions.

3.5. Hybrid Jacket vs. Hybrid Monopiles

This research performed a comparative analysis of the results regarding the damage number and the visual classification with those obtained for the (hybrid) monopile setup by [33], as the test settings and hydrodynamic conditions were similar. The comparison enables a more comprehensive assessment of the structural effects on scour between such distinctly different foundation types.

Table 7 shows that the measured values under the least energetic hydrodynamic condition were very similar across all model configurations (jacket vs. monopile and hybrid jacket vs. hybrid monopile). Under the intermediate condition ($H_s = 0.11$ m), comparable damage numbers were only registered between the jacket-monopile pair. As for the three highest wave-tested cases, the jacket/hybrid jacket configurations have substantially higher $S_{3D,measured}$ values in comparison to their monopile counterpart. These results are consistent with the findings of ref. [14], who studied jackets in current-only conditions, and ref. [23], who performed tests with wave-only scenarios. Conversely, it differs from the results stated by [19], whose experiments involved perpendicular wave-current alignments. Given that the present study employed collinear wave-current and wave-only conditions, the results may suggest that flow direction has a significant impact on the sediment-structure-flow interaction, a factor that warrants further investigation.

Table 7. $S_{3D,measured}$ and visual damage comparison between (hybrid) jackets and (hybrid) monopile foundations.

Test	Jacket		Monopile [33]	
	$S_{3D,measured}$	Visual Classification	$S_{3D,measured}$	Visual Classification
WC_7	1.72	Static (3000 waves)	1.95	Dynamic (3000 waves)
WC_11	1.98	Static (3000 waves)	1.83	Dynamic (3000 waves)
WC_15.5	4.71	Dynamic (almost fails for 3000 waves)	2.87	Failure (1000 waves)
WI_14	3.96	Dynamic (3000 waves)	3.08	Dynamic (almost fails for 3000 waves)
WR_14	4.90	Dynamic (almost fails for 3000 waves)	3.18	Failure (1000 waves)
Hybrid_WC_7	3.65	Slightly dynamic (3000 waves)	3.25	Failure (2000 waves)
Hybrid_WC_11	10.40	Failure (1000 waves)	5.38	Failure (1000 waves)
Hybrid_WC_15.5	19.10		9.81	
Hybrid_WI_14	16.00		7.28	
Hybrid_WC_14	16.80		8.55	

Although differences in the damage number values were observed between both studies, the visual classification of the scour protections in both studies (Table 7) revealed that the characteristics of the protection setup applied to the (hybrid) jacket exhibited an overall enhanced performance. For the jacket, the protection withstood the full test

duration, whereas in ref. [33], failures occurred for the WC_15.5 and WR_14 tests within the first 1000 waves. A similar trend was observed for the WC_7 test in the hybrid jacket, where the protection withstood the complete 3000-wave test. In contrast, the protection used for the hybrid monopile failed prematurely. These performance improvements can be attributed to the increased protection thickness used for the (hybrid) jackets— $3D_{n50}$ over most of the footprint area and locally reinforced to $5D_{n50}$ at each pile, following the recommendations proposed by [20,31]—when compared to the $t_s = 2.5D_{n50}$ protection tested by [33].

Nevertheless, even with the thicker armour layer, the damage numbers recorded under the more energetic wave conditions for the hybrid jacket were nearly twice those registered for the hybrid monopile. The amplification of the damage rate between both hybrid structures is in line with the severe armour layer damage, sediment erosion, and local seabed sinking observed beneath and around the filter layer—effects even more pronounced than those observed for the hybrid monopile. These results highlight the intricate hydrodynamic interactions and increased turbulence generated by hybrid structures, underscoring the need for tailored scour design guidelines for hybrid and geometrically complex offshore foundations.

3.6. Wave Transmission (K_t) and Wave Reduction (K_{Red}) Coefficients

The primary objective of this experimental study was to evaluate the damage to the scour protection of two different types of foundations. However, incorporating a WEC to transform a jacket foundation into a hybrid jacket revealed significant variations in flow patterns and hydrodynamic behaviour. Since the study did not target the mechanical-power performance of the WEC, parameters such as captured energy efficiency or power per unit front were not evaluated. Instead, simplified hydrodynamic interactions—namely the wave transmission coefficient (K_t), which compares seaside and leeside wave heights for each test, and the wave reduction coefficient (K_{Red}), which compares wave heights between jacket-only and hybrid jacket configurations under similar conditions—were employed to quantify the influence of both foundations on wave attenuation.

For jacket-only tests, the K_t values remained slightly above 100% (Table 8), with deviations ranging from 1.4% to 7.5%. Although the upper truss was expected to obstruct flow and slightly reduce leeward wave height, the structure's open cross-section likely facilitated near-complete wave propagation, confirming its limited wave-sheltering capacity. In contrast, the hybrid jacket with the integrated WEC achieved a pronounced reduction in K_t , particularly under higher wave heights, with up to 27% attenuation on the leeward side. These reductions were achieved using a simplified mechanical actuation system for the WEC paddles, indicating that a fully operational power take-off (PTO) system could further enhance attenuation. The observed trends are consistent with the findings of ref. [33], reinforcing that hybridisation can be effectively extended not only to monopiles but to more complex foundation geometries. Such configurations enhance dissipative capacity, increase wave absorption, and reduce transmitted wave energy. Nevertheless, a trade-off was identified: the hybrid jacket induced higher turbulence magnitudes and enhanced flow pattern contraction, which were responsible for the significant increase in the damage measured at the scour protection system.

Regarding the wave reduction coefficient, most seaside K_{Red} values for the hybrid jacket (Table 9) were negative, indicating local wave amplification of up to 10%. This effect is likely due to intense scour erosion that lowered the seabed, thereby increasing local water depth and enabling larger, non-breaking waves. Conversely, the leeside K_{Red} values consistently demonstrated substantial reductions in wave height—up to 33%—in line with the results reported by [33]. These findings highlight the potential of WECs

as multifunctional components in offshore infrastructure, serving not only as renewable energy devices but also as protective elements that mitigate wave energy and coastal erosion [3,32]. However, the optimisation and strategic integration of PTO systems remain crucial to address the scour intensification associated with WECs. While the WEC reduced transmitted wave height, it simultaneously enhanced scour damage to the armour layer. This outcome suggests that both the paddle's rotational angle and its clearance from the seabed are critical design parameters to mitigate excessive scour or structural damage.

Table 8. Wave transmission coefficients (K_t).

Test	N	K_t (%)
J_WC_7_1000	1000	102.9
J_WC_7_2000	1000	104.4
J_WC_7_3000	1000	101.4
J_WC_11_1000	1000	105.0
J_WC_11_2000	1000	104.9
J_WC_11_3000	1000	104.7
J_WC_15.5_1000	1000	100.7
J_WC_15.5_2000	1000	100.0
J_WC_15.5_3000	1000	100.0
J_WI_14_1000	1000	102.9
J_WI_14_2000	1000	105.2
J_WI_14_3000	1000	100.0
J_WR_14_1000	1000	104.3
J_WR_14_2000	1000	106.5
J_WR_14_3000	1000	107.5
JH_WC_7_1000	1000	95.6
JH_WC_7_2000	1000	97.1
JH_WC_7_3000	1000	93.0
JH_WC_11_1000	1000	82.9
JH_WC_15.5_1000	1000	73.4
JH_WI_14_1000	1000	73.9
JH_WR_14_1000	1000	78.2

Table 9. Wave reduction coefficients (K_{Red}).

Test	N	Seaside K_{Red} (%)	Leeside K_{Red} (%)
J_WC_7 vs. JH_WC_7	1000	1.5	9.2
	1000	−1.4	6.0
	1000	−2.8	6.1
J_WC_11 vs. JH_WC_11	1000	−9.9	14.1
J_WC_15.5 vs. JH_WC_15.5	1000	−5.8	29.2
J_WI_14 vs. JH_WI_14	1000	−4.2	33.3
J_WR_14 vs. JH_WR_14	1000	−6.1	25.2

The same conclusion was reported by [44], who implemented an OSWEC on the seabed as a protective element for pipelines, observing that the variation in the angle between the flap and the seabed affected the scour rates. When a smaller rotational amplitude around the vertical axis was used, which limited oscillatory motion and velocity, scour depths were reduced. Regarding converter's tip clearance—defined as the vertical distance between a

rotating blade/paddle and the seabed—ref. [45–47] investigated the effect of tip clearance on scour development in tidal-current turbines. Both reported that the converter enhanced local velocities, downflow, and horseshoe vortices, thus increasing scour. According to ref. [46], scour was intensified by 10–20% in extent and 30% in depth. It was also found that scour increased more rapidly with smaller tip clearances. However, the equilibrium scour depth was independent of tip clearance, indicating that further reduction in distance beyond a threshold had a negligible effect on scour progression.

4. Conclusions

This research characterises scour in riprap-protected jackets and hybrid jackets. The primary aim was to evaluate the performance of scour protection systems for jackets and hybrid jackets, and to clarify the governing scour mechanisms, damage progression, and hydrodynamic interactions for both types of structures. The research seeks to understand how local and global scour evolve at different locations and rates under the influence of a WEC. By comparing these results with those observed by [33] for monopiles and hybrid monopiles, this study provides valuable insights to guide future research in the marine harvesting technologies and offers a critical assessment of current design limitations for offshore foundations with a complex geometry.

As one of the novelties, the results of experimental testing of protected hybrid jacket foundations revealed that, although the WEC successfully attenuated incident hydrodynamic conditions—lowering the leeward wave heights by up to 33%—the oscillatory motion of the converter’s paddles paradoxically amplified local scour mechanisms. The generation of complex flow patterns, more specifically, horseshoe vortices, lee-wake vortices, streamline contractions, and downflow, resulted in severe, irreversible damage to the scour protection. This highlights a crucial design trade-off: the energy-harvesting benefit of the WEC comes at the cost of structural stability for the foundation and its scour protection.

Regarding the differences between the jacket and hybrid jacket foundation tests, the study shows that the scour protections designed for the jackets, following the recommendations by [20,21,31], have retained their structural integrity, proving that both recommendations offer a valuable starting point for future design guidelines. However, the results also highlight that the exact same protection system applied to the hybrid configuration is highly vulnerable. The protection system on hybrid jackets often sustained premature failure, typically within the first 1000 waves, indicating that the WEC-flow complex relation is a key driver of irreversible damage.

Regarding the S_{3D} measured for both foundations, the results demonstrate that the design equation developed for monopile foundations (Equation (1)) is insufficient to capture the intricacies of complex and hybrid foundations, raising concerns about the feasibility and conservatism of the design principles presented by [5].

As an alternative, the overlapping-circle methodology developed by [34] was successfully adapted and validated for complex foundations and non-standard scour protection geometries. It allowed an accurate quantification of the damage spatial distribution. The analysis also confirmed a strong dependency of $S_{3D,max}$ on the grid ratio ($\eta_{S3D,grid}$) and the selected sub-area size (A_{sub}), consistent with the findings reported by [34]. The grid ratios of 1/8 and 1/4, corresponding to sub-areas of $8D_{n50}^2$ and $4D_{n50}^2$, respectively, were found to be the most suitable for estimating the damage number, within a similar range observed by [33]. Although the $\eta_{S3D,grid} = 1/4$ ($A_{sub} = 4D_{n50}^2$) was identified as the most representative for assessing protection failure, in line with the failure criterion proposed by [6].

Alternative metric limits, such as $S/t_s > 1.0$ and $S_{3D}/n_s > 1.0$, were found to provide a more representative assessment of protection failure than $S_{3D} > 1.0$, proposed by [5].

Both metrics appear to be closer to the experimentally observed behaviours and visual classifications attributed to each test, thus suggesting a need to reconsider the limits as a function of the protection thickness. Nonetheless, the exact S_{3D} , S/t_s , or S_{3D}/n_s value for the static-to-dynamic threshold needs to be reconsidered and defined through further testing.

The interpretations of these results must be contextualised within specific experimental limitations to avoid overgeneralization.

- Scale effects: the use of the Froude similitude with a 1:50 geometric scale inevitably introduces some scale effects regarding viscous forces and sediment size. While the R_e number was maintained in a range to restrain vortex shedding discrepancies, as suggested by [35], the scaling of granular bed material may not perfectly replicate prototype sediment transport regimes.
- OSWEC model: The WEC selected for the experimental study was modelled as a simplified oscillating paddle system. While macroscopically this reproduces the potential effects and influences of the device in enhancing flow and scour mechanisms, it does not fully capture the real effects of damping and control strategies of a full-scale device with a fully functional PTO system.

Overall, the authors believe that this study contributes to a broader comprehension of hydrodynamic interactions in complex and hybrid offshore foundations, emphasising the need to revise existing scour protection design frameworks. Although based on a limited dataset, the results clearly indicate the necessity of a uniform and optimised design criterion that integrates structural complexities, dynamic load interactions, and energy-harvesting components. These approaches are essential to ensure that resilient, efficient, and protective solutions continue to be developed for future offshore and marine renewable infrastructures.

The following points summarise the key contributions of this research:

- Scour protection applied to a hybrid jacket-WEC system: comparative evaluation of the S_{3D} between a jacket and a hybrid jacket foundation. Results demonstrated that paddle-based WECs intensify scour due to the influence of the paddle's oscillatory motion, thereby enhancing turbulence and flow patterns, despite its capacity to attenuate wave heights up to 33%.
- Overlapping-circle 3D method implemented to a complex geometry foundation: the research successfully adapted and implemented the methodology developed by [34] to a jacket foundation, a structure with higher complexity when compared to a monopile, and to a square scour protection (different from the typical circular shape). The method demonstrated a high-resolution scour quantification capability through a highly accurate computation of S_{3D} , thereby providing valuable insights into complex and hybrid configurations. Despite the sensitivity to the grid ratio, results suggest an ideal range between 1/8 and 1/4. However, low grid ratios present some difficulties in properly representing overlapping elements near the corners and around the piles in complex foundations/protections. Therefore, the 1/4 ratio remains the most reliable, consistent with the findings disclosed by [6,34];
- Scour protection design predictive formulas limitations: the study's findings raise some questions regarding the underestimation and application of current design standards, developed primarily for monopiles, which do not account for increased flow and structural complexity of other structures and hybrid configurations. Hybrid jackets failed prematurely, with massive damage rates, within the first 1000 waves. The results emphasise that currently, there is no methodology capable of effectively considering the additional loads caused by the interaction between sediment flow, WEC, and the structure.

- Alternative scour metrics for scour protection performance: the S/t_s and S_{3D}/n_s parameters, proposed as alternatives by [33] to better quantify and evaluate the performance of scour protections in complex offshore settings, can successfully identify when a protection is dynamic, closer to failure, and when failure occurs. These measurements shift the evaluation focus from the foundation to the armour layer itself, providing a clearer picture of relative performance. Both indicators outperform traditional parameters such as the S/D and the $S_{3D} > 1.0$ threshold. However, the static limit may need to be reconsidered, as it can be overly conservative and result in thicker protections.

To further advance the understanding of scour processes in hybrid offshore foundations, future research should strategically expand the experimental test matrix to encompass a broader spectrum of hydrodynamic conditions, alternative scour protection layouts, various WEC devices, and variations in some structural parameters. One key component could be related to the influence of hydrodynamic directionality. This experimental campaign used only co-directional wave-current conditions due to the facilities' constraints. While this configuration generally represents the most critical loading case, the offshore and marine environments often involve complex, multi-directional flow interactions. Consequently, the influence of transverse and counter-directional wave-current regimes on the damage patterns and distribution for protected complex and hybrid foundations should be addressed to determine if the asymmetry of the incoming flow induces preferential damage zones and different S_{3D} values from those observed in co-directional regimes. Expanding these elements will be fundamental to developing comprehensive datasets that reflect the entire range of scour and damage mechanisms in such complex and hybrid systems. These initiatives could be critical to increase knowledge and optimise the next generation of design approaches and predictive models that incorporate hydrodynamic–structural coupling and energy-harvesting dynamics. Such developments could be crucial to achieving safer, more efficient, and sustainable offshore solutions, ultimately supporting the transition towards a more resilient marine renewable energy sector.

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Abbreviations

The following abbreviations are used in this manuscript:

ADV	Acoustic Doppler Velocimeter
A_{pile_jacket}	Overlapping-circle sub-area equivalent to jacket's pile area
A_{sub}	Area of the overlapping-circle sub-areas
a_0, a_2, a_3	Regression fitting coefficients
a_1, a_4	Coefficient for hydrodynamic conditions
b_0	Regression fitting coefficient
D_{jacket}	Diameter of jacket piles
D_{n50}	Nominal stone diameter of the scour protection
$D_{v,i}$	Incremental erosion depth
D_{15}	15th percentile of scour protection material grading
D_{85}	85th percentile of scour protection material grading
DOF	Degrees of freedom
DTM	Digital Terrain Model
d	Water depth
d_{16}	16th percentile of sediments
d_{50}	Mean diameter of sediments
d_{84}	84th percentile of sediments
F_r	Froude number
FOSWEC	Floating Oscillating Surge Wave Energy Converter
g	Gravitational acceleration
H	Wave height
H_{m0}	Spectral significant wave height
H_s	Significant wave height
H_{rms}	Root-mean square wave height
J	Jacket
JH	Hybrid jacket
JONSWAP	Joint North Sea Wave Project
K_{Red}	Wave reduction coefficient
K_t	Wave transmission coefficient
KC	Keulegan–Carpenter number (wave contribution)
LCoE	Levelized Cost of Energy
N	Number of waves
n_s	Number of rock stone sizes (layers)
OSWEC	Oscillating Surge Wave Energy Converter
OWE	Offshore wind energy
OWF	Offshore Wind Foundation
PTO	Power-take off
p	Multiplication factor for overlapping-circle sub-area
R_{circle}	Radius of overlapping-circle sub-area
R_e	Reynolds number
S	Scour depth
S_{eq}	Equilibrium scour depth
S_{end}	End scour depth
S/D	Relative scour depth
S/t_s	Scour depth relative to the scour protection thickness
S_{3D}	Damage number
$S_{3D,hybrid}$	Damage number at hybrid jacket
$S_{3D,jacket}$	Damage number at jacket foundations
$S_{3D,max}$	Damage number (maximum)
$S_{3D,measured}$	Damage number (measured)
$S_{3D,predicted}$	Damage number (predicted)

S_{3D}/n_s	Damage number relative to the number of rock stone sizes (layers)
$S_{3D,measured}/n_s$	Measured damage number relative to the number of rock stone sizes (layers)
s	Specific density (ρ_s/ρ_w)
T^*	Dimensionless time scale
$T_{m-1,0}$	Energy wave period
T_p	Wave peak period
t_s	Scour protection thickness
U_c	Depth-averaged current velocity
U_{cw}	Wave-current velocity ratio
U_m	Wave orbital bottom velocity
$V_{A,i}$	Cumulative dimensionless erosion volume
V_{circle}	Volume of overlapping-circle sub-area
WC	Waves-and-currents
WEC	Wave Energy Converter
WI	Irregular waves
WR	Regular waves
w_s	Settling velocity
$\Delta S_{3D}/n_s$	Damage increase ratio
$\eta_{S3D,grid}$	Grid ratio
ρ_s	Density of rock material
ρ_w	Water mass density
σ_s	Standard deviation of sediments
γ	Wave spectrum peak enhancement factor

Appendix A. Jacket and Hybrid Jacket S_{3D} Results ($A_{sub} = 4D_{n50}^2$)

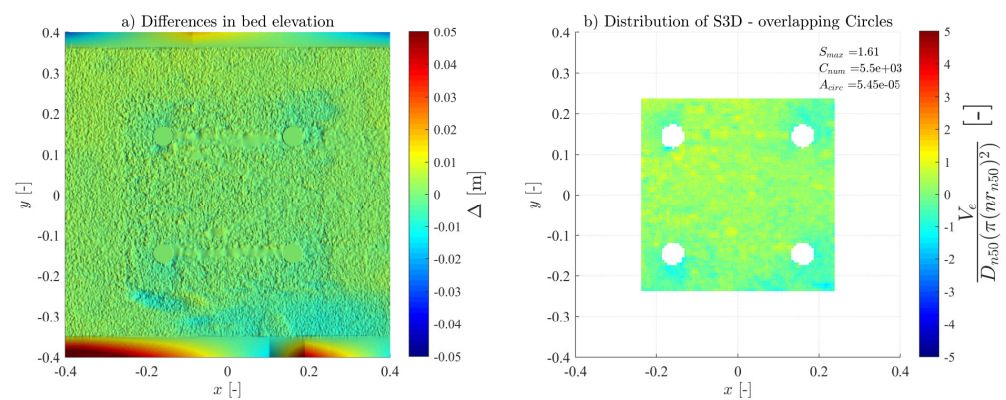


Figure A1. J_WC_7_1000: (a) DTM and (b) S_{3D} distribution—waves and currents from left to right.

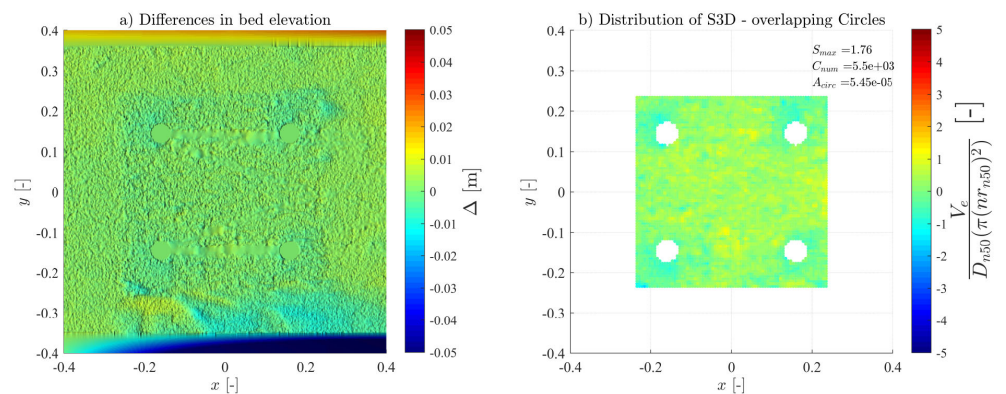


Figure A2. J_WC_7_2000: (a) DTM and (b) S_{3D} distribution—waves and currents from left to right.

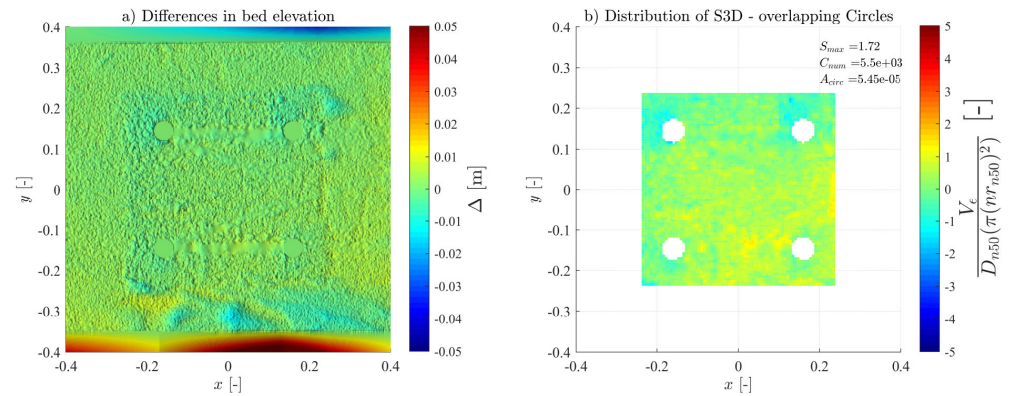


Figure A3. J_WC_7_3000: (a) DTM and (b) S_{3D} distribution—waves and currents from left to right.

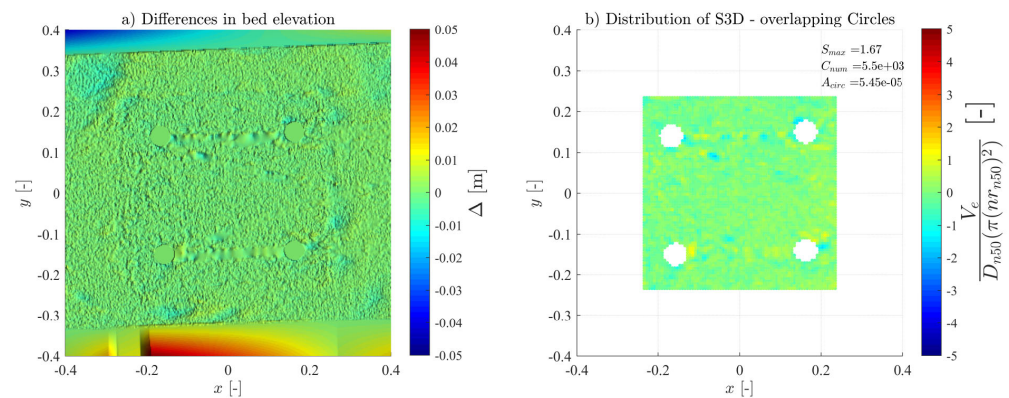


Figure A4. J_WC_11_1000: (a) DTM and (b) S_{3D} distribution—waves and currents from left to right.

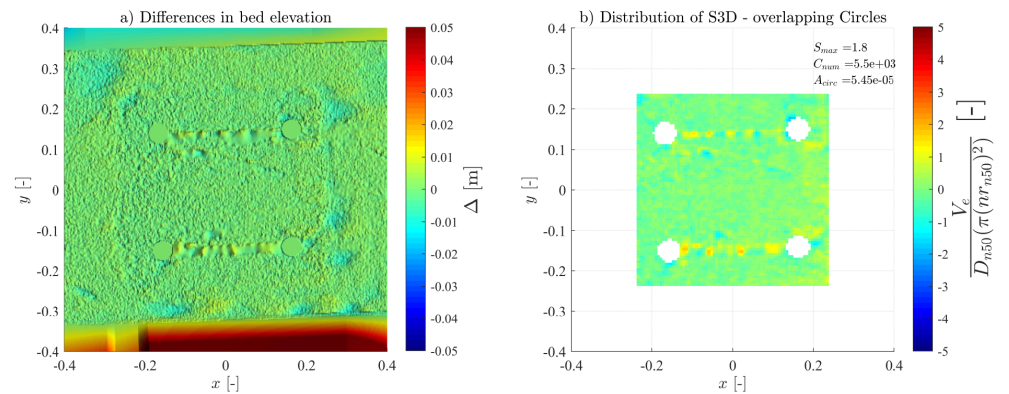


Figure A5. J_WC_11_2000: (a) DTM and (b) S_{3D} distribution—waves and currents from left to right.

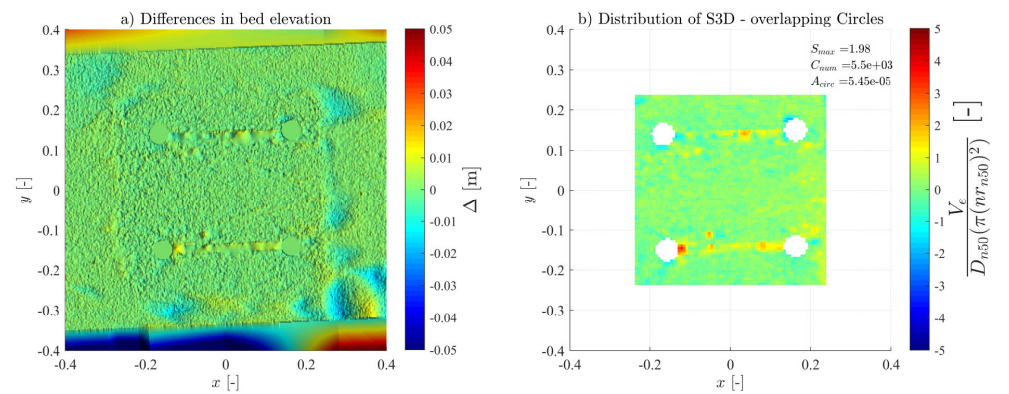


Figure A6. J_WC_11_3000: (a) DTM and (b) S_{3D} distribution—waves and currents from left to right.

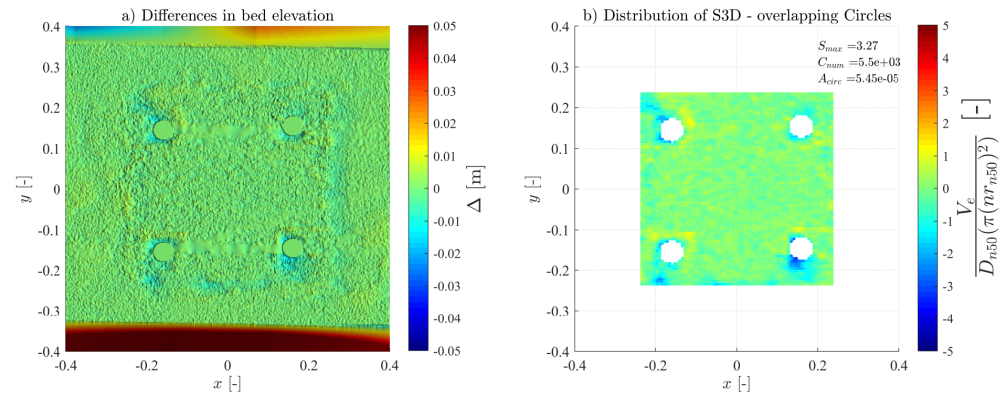


Figure A7. J_WC_15.5_1000: (a) DTM and (b) S_{3D} distribution—waves and currents from left to right.

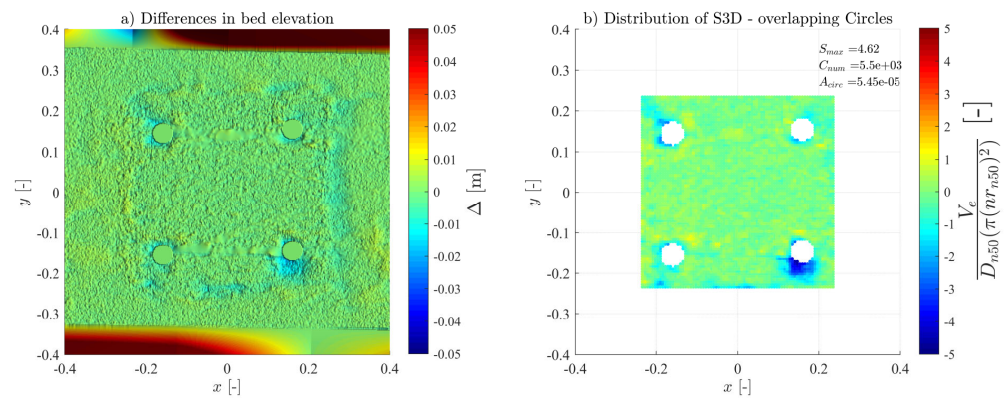


Figure A8. J_WC_15.5_2000: (a) DTM and (b) S_{3D} distribution—waves and currents from left to right.

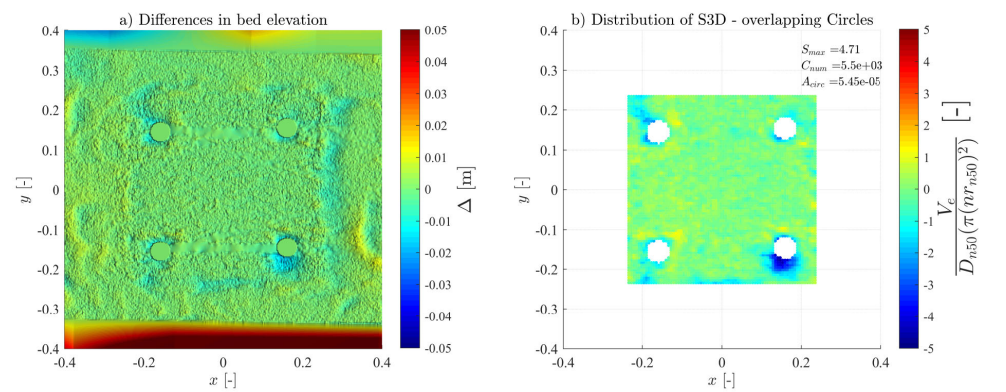


Figure A9. J_WC_15.5_3000: (a) DTM and (b) S_{3D} distribution—waves and currents from left to right.

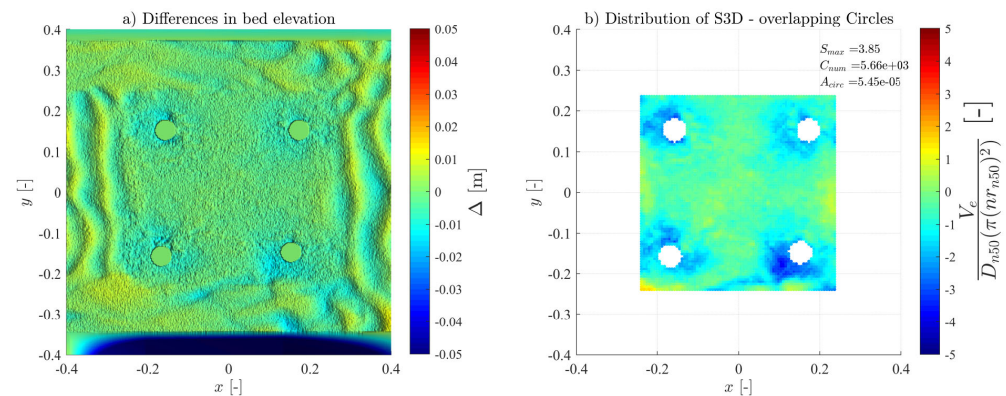


Figure A10. J_WI_14_1000: (a) DTM and (b) S_{3D} distribution—waves from left to right.

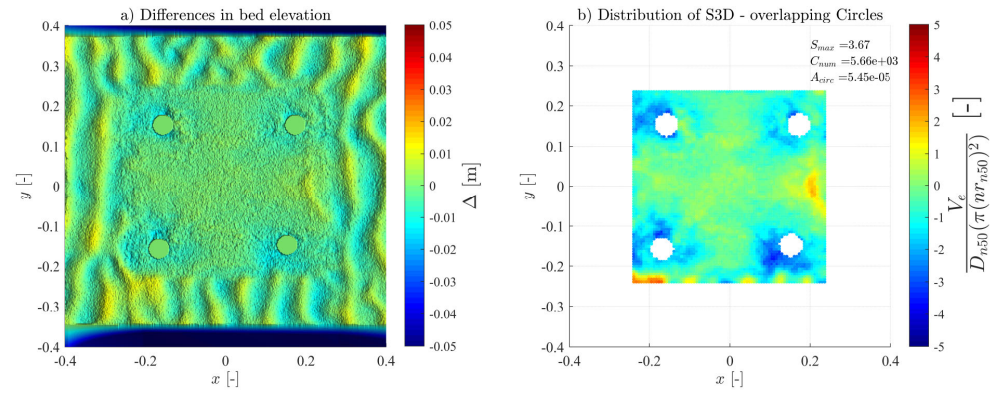


Figure A11. J_WI_14_2000: (a) DTM and (b) S_{3D} distribution—waves from left to right.

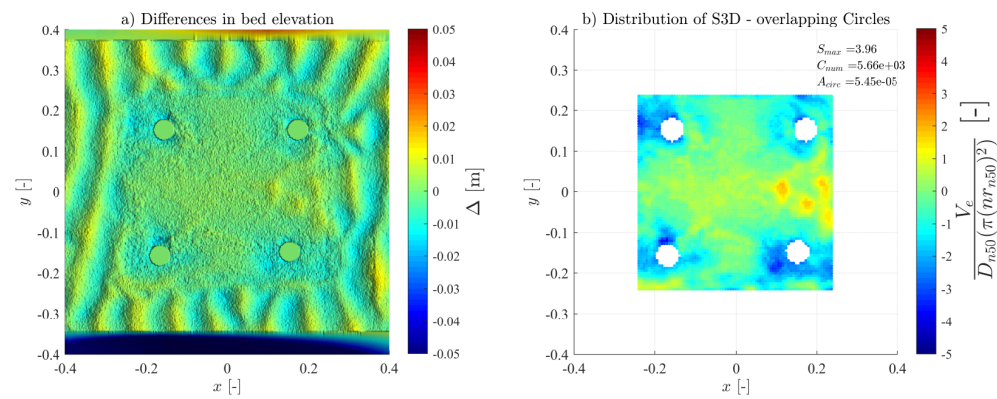


Figure A12. J_WI_14_3000: (a) DTM and (b) S_{3D} distribution—waves from left to right.

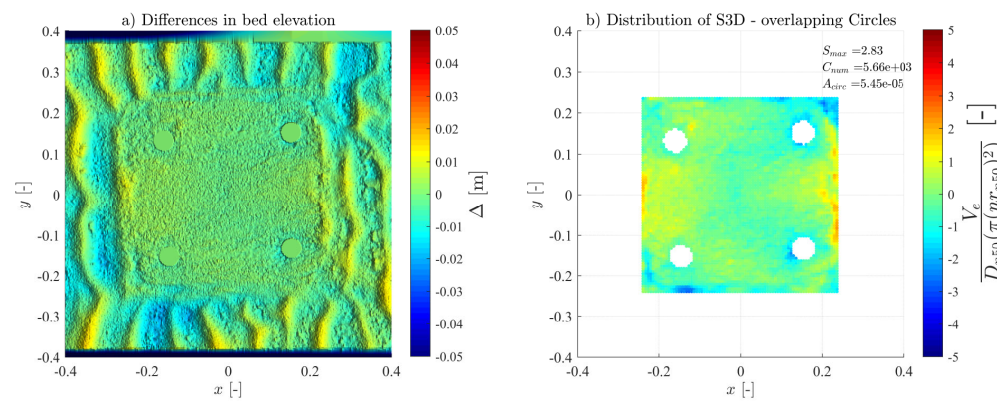


Figure A13. J_WR_1000: (a) DTM and (b) S_{3D} distribution—waves from left to right.

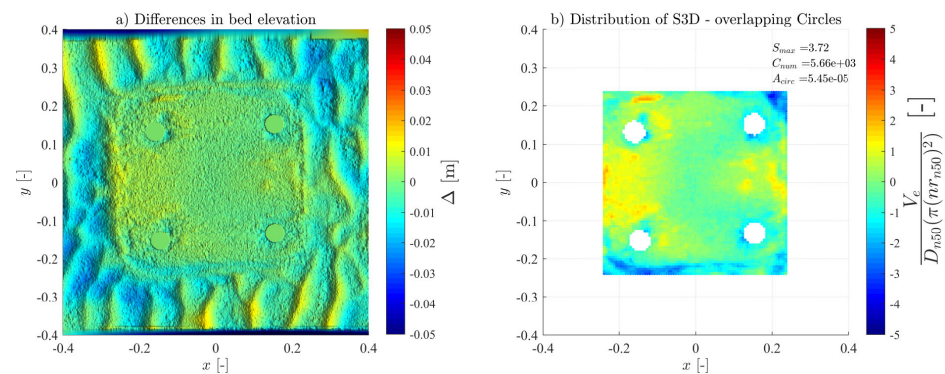


Figure A14. J_WR_2000: (a) DTM and (b) S_{3D} distribution—waves from left to right.

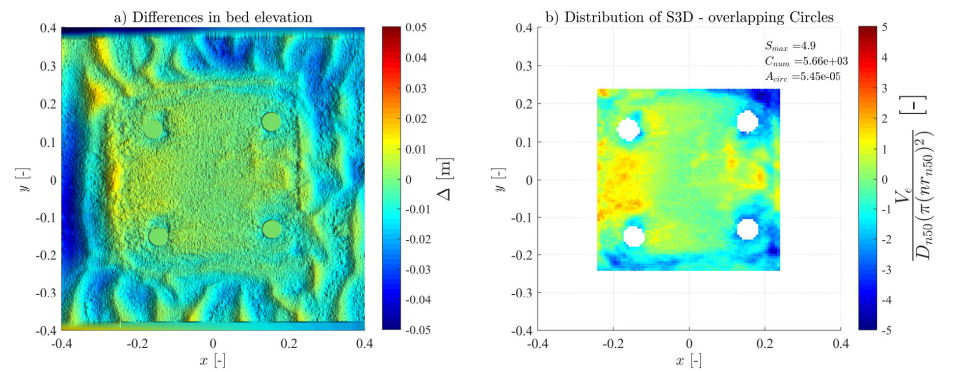


Figure A15. J_WR_3000: (a) DTM and (b) S_{3D} distribution—waves from left to right.

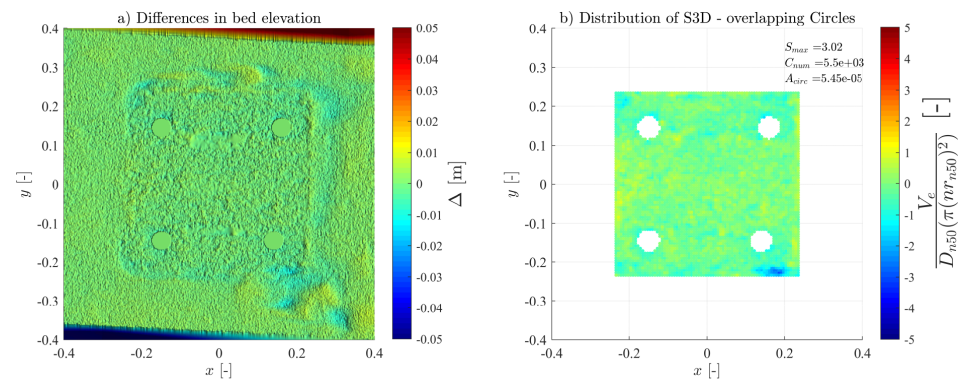


Figure A16. JH_WC_7_1000: (a) DTM and (b) S_{3D} distribution—waves and currents from left to right.

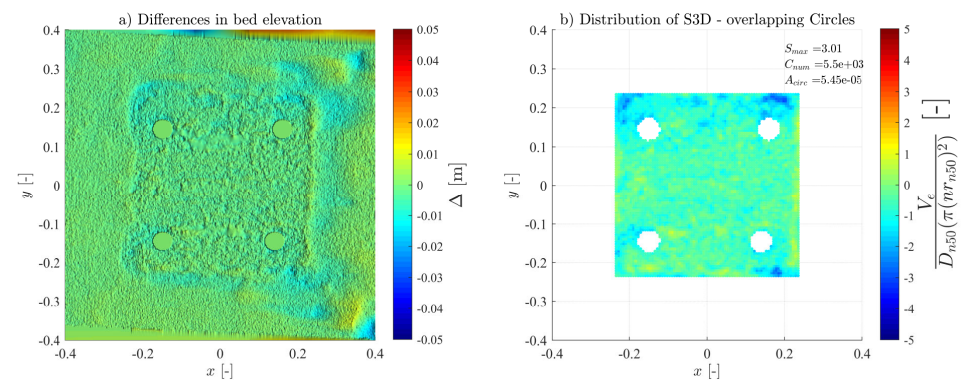


Figure A17. JH_WC_7_2000: (a) DTM and (b) S_{3D} distribution—waves and currents from left to right.

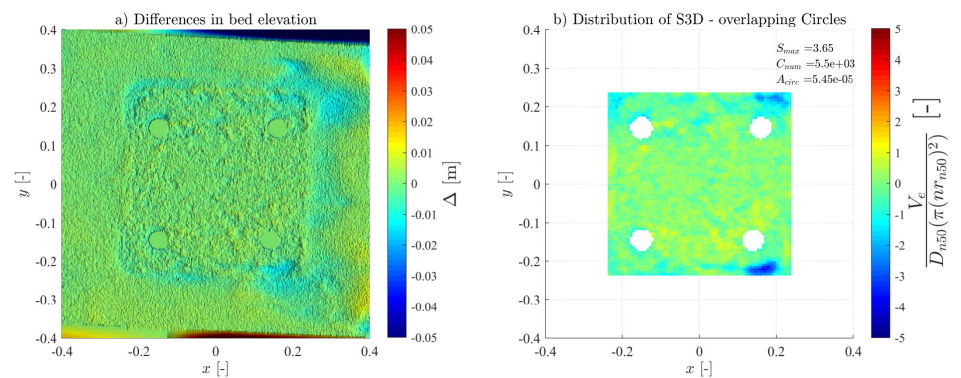


Figure A18. JH_WC_7_3000: (a) DTM and (b) S_{3D} distribution—waves and currents from left to right.

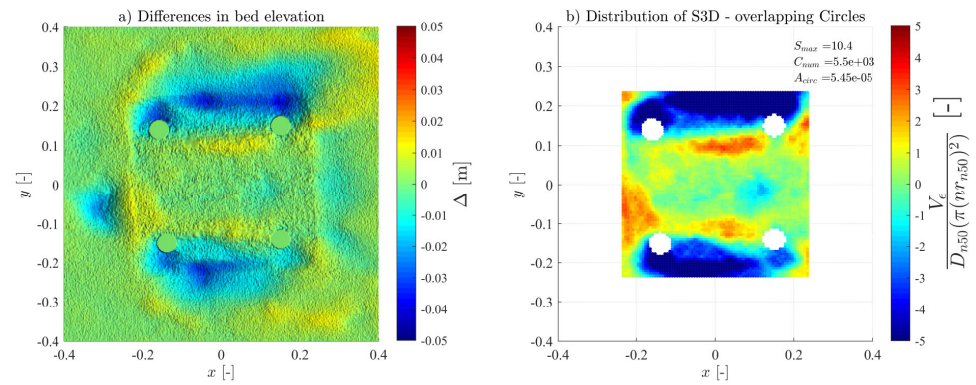


Figure A19. JH_WC_11_1000: (a) DTM and (b) S_{3D} distribution—waves and currents from left to right.

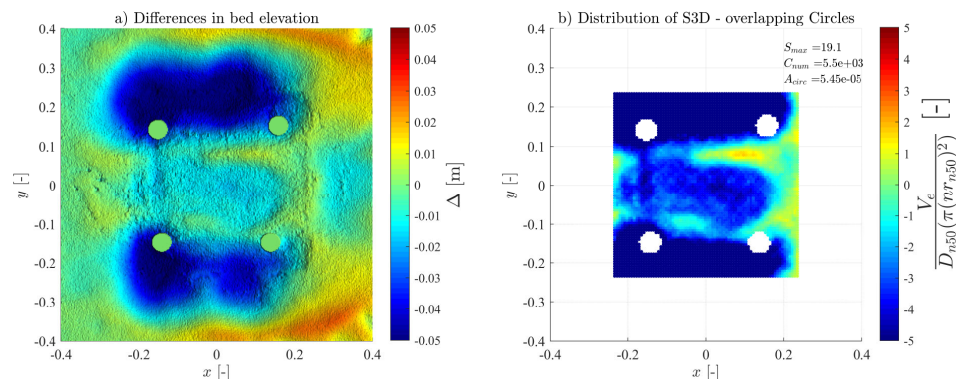


Figure A20. JH_WC_15.5_1000: (a) DTM and (b) S_{3D} distribution—waves and currents from left to right.

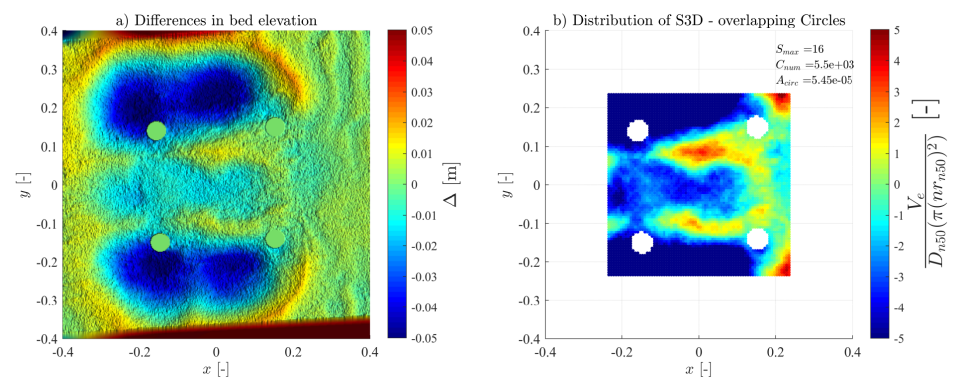


Figure A21. JH_WI_14_1000: (a) DTM and (b) S_{3D} distribution—waves from left to right.

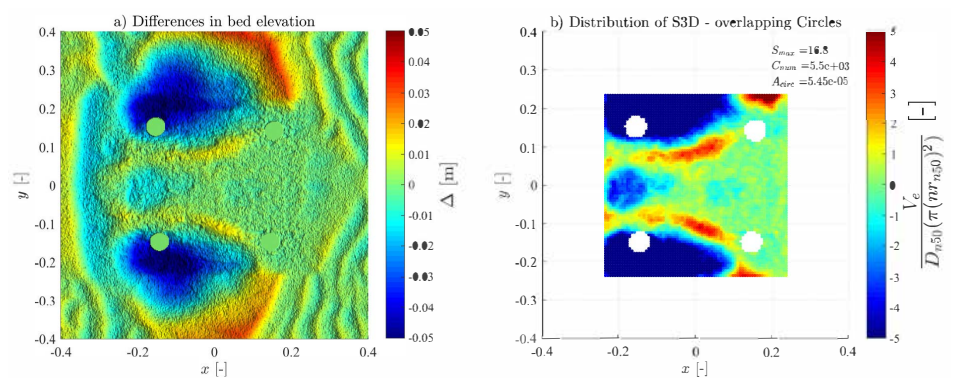


Figure A22. JH_WR_14_1000: (a) DTM and (b) S_{3D} distribution—waves from left to right.

Appendix B. Jacket and Hybrid Foundations S_{3D} Results for Different Grid Ratios ($\eta_{S3D,grid}$)

Table A1. $S_{3D,max}$ for different grid ratios ($\eta_{S3D,grid}$)—(A): J_WC_7_3000; (B): J_WC_11_3000; (C) J_WC_15.5_3000; (D) J_WI_14_3000; (E) J_WR_14_3000.

Jacket					(A)	(B)	(C)	(D)	(E)
A_{sub}	Value [m ²]	$\eta_{S3D,grid}$	p Value	R_{circle} [m]	$S_{3D,max}$				
D_{n50}^2	1.362×10^{-5}	1.000	1.1284	2.082×10^{-3}	2.05	2.62	5.66	5.14	6.14
$1.111D_{n50}^2$	1.513×10^{-5}	0.900	1.1894	2.194×10^{-3}	2.02	2.60	5.92	5.65	6.26
$1.5D_{n50}^2$	2.042×10^{-5}	0.667	1.3820	2.550×10^{-3}	2.01	2.54	5.37	5.14	5.98
$2D_{n50}^2$	2.723×10^{-5}	0.500	1.5958	2.944×10^{-3}	1.71	2.16	5.58	4.56	5.40
$3D_{n50}^2$	4.085×10^{-5}	0.333	1.9544	3.606×10^{-3}	1.76	2.04	5.29	5.04	5.33
$4D_{n50}^2$	5.446×10^{-5}	0.250	2.2568	4.164×10^{-3}	1.72	1.98	4.71	3.96	4.90
$5D_{n50}^2$	6.808×10^{-5}	0.200	2.5231	4.655×10^{-3}	1.63	1.75	4.96	3.97	5.34
$6D_{n50}^2$	8.170×10^{-5}	0.167	2.7640	5.099×10^{-3}	1.53	1.70	4.38	4.00	4.64
$7D_{n50}^2$	9.531×10^{-5}	0.143	2.9854	5.508×10^{-3}	1.48	1.52	4.20	4.07	4.95
$8D_{n50}^2$	1.089×10^{-4}	0.125	3.1915	5.888×10^{-3}	1.55	1.69	4.47	4.05	4.93
$9D_{n50}^2$	1.225×10^{-4}	0.111	3.3851	6.246×10^{-3}	1.30	1.45	4.50	3.88	4.76
$10D_{n50}^2$	1.362×10^{-4}	0.100	3.5682	6.583×10^{-3}	1.14	1.28	4.05	3.81	4.49
$16D_{n50}^2$	2.179×10^{-4}	0.063	4.5135	8.327×10^{-3}	1.13	1.10	4.49	3.90	4.54
$20D_{n50}^2$	2.723×10^{-4}	0.050	5.0463	9.310×10^{-3}	1.18	1.08	4.24	3.81	4.47
$25D_{n50}^2$	3.404×10^{-4}	0.040	5.6419	1.041×10^{-2}	1.07	0.96	3.58	3.45	4.59
A_{pile_jacket}	4.909×10^{-3}	0.02774	6.7751	1.250×10^{-2}	0.95	0.82	4.24	3.21	4.54

Table A2. $S_{3D,max}$ for different grid ratios ($\eta_{S3D,grid}$)—(A): JH_WC_7_3000; (B): JH_WC_11_1000; (C) JH_WC_15.5_1000; (D) JH_WI_14_1000; (E) JH_WR_14_1000.

Hybrid Jacket					(A)	(B)	(C)	(D)	(E)
A_{sub}	Value [m ²]	$\eta_{S3D,grid}$	p Value	R_{circle} [m]	$S_{3D,max}$				
D_{n50}^2	1.362×10^{-5}	1.000	1.1284	2.082×10^{-3}	4.20	13.00	24.80	21.20	22.50
$1.111D_{n50}^2$	1.513×10^{-5}	0.900	1.1894	2.194×10^{-3}	4.13	12.10	23.60	19.20	21.20
$1.5D_{n50}^2$	2.042×10^{-5}	0.667	1.3820	2.550×10^{-3}	4.10	13.70	22.20	20.20	21.40
$2D_{n50}^2$	2.723×10^{-5}	0.500	1.5958	2.944×10^{-3}	4.33	12.30	21.10	19.90	20.60
$3D_{n50}^2$	4.085×10^{-5}	0.333	1.9544	3.606×10^{-3}	3.80	11.50	20.80	19.90	19.20
$4D_{n50}^2$	5.446×10^{-5}	0.250	2.2568	4.164×10^{-3}	3.65	10.30	18.80	16.00	16.80
$5D_{n50}^2$	6.808×10^{-5}	0.200	2.5231	4.655×10^{-3}	4.16	12.40	20.30	18.70	18.30
$6D_{n50}^2$	8.170×10^{-5}	0.167	2.7640	5.099×10^{-3}	3.47	10.30	18.20	16.30	17.00
$7D_{n50}^2$	9.531×10^{-5}	0.143	2.9854	5.508×10^{-3}	3.68	9.35	18.30	16.30	17.00
$8D_{n50}^2$	1.089×10^{-4}	0.125	3.1915	5.888×10^{-3}	3.52	10.20	18.80	16.10	16.40
$9D_{n50}^2$	1.225×10^{-4}	0.111	3.3851	6.246×10^{-3}	3.60	9.94	18.40	15.50	16.40
$10D_{n50}^2$	1.362×10^{-4}	0.100	3.5682	6.583×10^{-3}	3.51	9.89	18.00	15.40	16.00
$16D_{n50}^2$	2.179×10^{-4}	0.063	4.5135	8.327×10^{-3}	3.27	9.81	18.20	14.70	15.90

Table A2. Cont.

Hybrid Jacket					(A)	(B)	(C)	(D)	(E)
A_{sub}	Value [m ²]	$\eta_{S3D,grid}$	p Value	R_{circle} [m]	$S_{3D,max}$				
$20D_{n50}^2$	2.723×10^{-4}	0.050	5.0463	9.310×10^{-3}	3.36	9.65	17.30	15.30	15.90
$25D_{n50}^2$	3.404×10^{-4}	0.040	5.6419	1.041×10^{-2}	3.39	9.76	17.50	14.80	15.50
A_{pile_jacket}	4.909×10^{-3}	0.02774	6.7751	1.250×10^{-2}	3.17	9.20	17.10	14.40	15.40

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Appendix V – Chambel *et al.* (2026b)



Maritime Engineering

New Damage Quantification Method for Protected Complex Offshore Foundations: Statistical Analysis

MAEN-2026-006-R1 | Paper

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Submitted by: João Chambel, Tiago Ferradosa, Xavier Romão, Mahdi Alemi, Francisco Taveira-Pinto, Pedro Lomonaco

Keywords: STATISTICAL ANALYSIS, DAMAGE NUMBER, SCOUR PROTECTION, COMPLEX FOUNDATIONS, OFFSHORE WIND ENERGY, OFFSHORE ENGINEERING

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New Damage Quantification Method for Protected Complex Offshore Foundations: Statistical Analysis

João Chambel (MSc) – Author 1 (corresponding author: up201304674@fe.up.pt)

- Hydraulics, Water Resources, and Environmental Division, Department of Civil and Georesources Engineering, Faculty of Engineering of the University of Porto (FEUP), Portugal & Interdisciplinary Centre of Marine and Environmental Research (CIIMAR), 4450-208 Matosinhos, Portugal (ORCID: 0000-0002-7314-4959).

Tiago Fazeres-Ferradosa (PhD) – Author 2

- Hydraulics, Water Resources, and Environmental Division, Department of Civil and Georesources Engineering, Faculty of Engineering of the University of Porto (FEUP), Portugal & Interdisciplinary Centre of Marine and Environmental Research (CIIMAR), 4450-208 Matosinhos, Portugal.

Xavier Romão (PhD) – Author 3

- CONSTRUCT, Department of Civil and Georesources Engineering, Faculty of Engineering of the University of Porto (FEUP), Portugal.

Mahdi Alemi (PhD) – Author 4

- Haedes, Kortewagenstraat 53b, 9230 Wetteren-ten-Ede, Belgium.

Francisco Taveira-Pinto (PhD) – Author 5

- Hydraulics, Water Resources, and Environmental Division, Department of Civil and Georesources Engineering, Faculty of Engineering of the University of Porto (FEUP), Portugal & Interdisciplinary Centre of Marine and Environmental Research (CIIMAR), 4450-208 Matosinhos, Portugal.

Pedro Lomonaco (PhD) – Author 6

- O.H. Hinsdale Wave Research Laboratory, College of Engineering, Oregon State University (OSU), Corvallis, Oregon, United States of America.

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Abstract

Accurate damage analysis of scour protections is crucial to ensuring the stability of offshore wind turbines. Traditional methodologies focus on fixed sub-areas of the protection, neglecting damage quantification in intersection zones, thereby increasing uncertainty in classifying the protection's stability. A recent overlapping methodology proved effective in damage characterisation for monopiles and standard protections. However, it remains sensitive to grid selection and restricted to circular protections. This research develops an improved analysis system for non-standard configurations, successfully applied to jacket foundations and square protections under combined wave-and-current conditions. The novel method accurately captured damage distribution, particularly within critical pile areas.

Statistical analysis revealed that maximum and minimum extreme values are highly sensitive to mesh resolution, whereas the mean remains invariant. A new framework was proposed, integrating two evaluation methodologies: a spatial/volumetric loss approach for assessing global scour, which aligns maximum damage with upper-bound percentiles; and a threshold calibration protocol for characterising local scour that effectively reduces sub-area dependency. This ensures a behavioural characterisation consistent with visual assessment across varying mesh resolutions. This combined method establishes the overlapping concept as a versatile approach for damage evaluation in various layouts of scour protections and complex offshore foundations.

Keywords

Statistical Analysis; Damage Number; Scour Protection; Complex Foundations; Offshore Wind Energy, Offshore Engineering, UN SDG 7, UN SDG 13.

List of notations

$A_{L\%}$	Acceptable spatial loss
A_{sub}	Area of the overlapping-circle sub-area
$A_{protection}$	Area of scour protection
C_f	Correction factor
D_{jacket}	Diameter of jacket piles
D_p	Monopile diameter
D_{n50}	Nominal stone diameter
D_{15}	15 th percentile of material grading
D_{85}	85 th percentile of material grading
d	Water depth
H_s	Significant wave height
KC	Keulegan-Carpenter number
n_s	Number of stone size layers
P_{99}	99 th percentile
P_{95}	95 th percentile

P_{90}	90 th percentile
R_{circle}	Radius of overlapping-circle sub-area
S_{3D}	Damage number
$S_{3D,FTE}$	Failure threshold estimation damage number (without correction factor)
$S_{3D,failure}$	Failure threshold damage number
$S_{3D,max}$	Maximum damage number
$S_{3D,mean}$	Mean damage number
$S_{3D,min}$	Minimum damage number
$S_{3D,static}$	Static threshold damage number
S_{3Dsub}	Damage number of sub-area
T_p	Wave peak period
t_s	Scour protection thickness
U_c	Depth-averaged current velocity
U_{cw}	Wave-current velocity ratio
V_e	Eroded volume
$V_{L\%}$	Acceptable volume loss
V_t	Total scour protection volume
$\eta_{S3D,grid}$	Grid Ratio
σ_{S3D}	Standard deviation of damage distribution
λ_{static}	Static threshold ratio

1. Introduction

As the offshore industry strives to meet net-zero emission targets by 2050, demand for wind energy generation continues to grow rapidly (WindEurope, 2021). To achieve the expected goals, offshore wind turbines are increasingly being deployed in deeper waters, where they encounter more intense hydrodynamic conditions, higher wind speeds, and reduced visual pollution. While monopiles are the most common foundation type, accounting for over 80% of installations (Chambel *et al.*, 2024), their feasibility in deeper waters is limited by structural constraints. Consequently, complex foundations, such as jackets, are becoming an alternative solution for deep-water sites due to their superior structural performance in harsh environments (Chen *et al.*, 2014, 2023, 2025a; Hao and Liu, 2017).

According to Matutano *et al.* (2013) and Bhattacharya (2014), the foundation accounts for approximately one-third of the overall investment of an offshore wind farm. Their stability is heavily reliant on scour protection systems, mainly riprap solutions, to prevent seabed erosion, one of the primary causes of interference with bearing capacity, ultimate, and service limit states (Sørensen and Ibsen, 2013; Saathoff *et al.*, 2024). To optimise costs, the industry has focused on transitioning from static to dynamic protection, where the rubble-mound material size is smaller and the controlled movement of armour layer units is allowed, without compromising the foundation's stability (Fazeres-Ferradosa *et al.*, 2021).

Recently, the concept of hybrid foundations has emerged and generated increasing interest, where the co-location of more than one harvesting technology can be an interesting solution to enhance energy production, optimise spatial utilisation of marine areas, and could help lower the levelized cost of energy (LCoE) – Chambel *et al.* (2025). However, existing scour protection design approaches do not account for the structural complexity and additional features of complex and hybrid foundations, such as bracings, joints, J-tubes, horizontal elements, and even wave energy converters (WEC) for the case of hybrid structures.

Implementing dynamic scour protections requires precise methodologies to quantify damage to the protection. The additional elements of complex foundations can significantly alter hydrodynamic conditions and turbulence, leading to increased local scour (Fazeres-Ferradosa *et al.*, 2021; Chambel *et al.*, 2024). The threshold of motion concept, Soulsby (1997), was commonly used in the design of static scour protections. The concept of dynamic protection was first introduced by den Boon *et al.* (2004), who proposed the stab parameter and defined failure as the exposure of the filter layer to an area equivalent to $4D_{n50}^2$ – comparable to a square of two-by-two D_{n50} (nominal median stone diameter) stones.

De Vos *et al.* (2012) noted that the stab parameter failed to predict some of the motions caused under different hydrodynamic conditions and proposed the three-dimensional damage number (S_{3D}), which was based on Van der Meer *et al.*'s (1988) two-dimensional damage number concept for breakwaters. The method of De Vos *et al.* (2012) consisted of dividing the scour protection into fixed sub-areas with the same area as the monopile cross-section. The damage number in each sub-area ($S_{3D,sub}$) was obtained as the ratio of the eroded volume (V_e) by the surface of the sub-area (A_{sub}) times D_{n50} , Equation (1). The protection should be classified into three different levels of damage: static ($S_{3D} < 0.25$), dynamic ($0.25 < S_{3D} < 1.0$), and failure ($S_{3D} > 1.0$).

$$S_{3D,sub} = \frac{V_e}{D_{n50} \cdot A_{sub}} \quad (1)$$

While this methodology enabled the assessment of damage in armour layers with dynamic stability, De Schoessiter *et al.* (2014), Whitehouse *et al.* (2014), and Fazeres-Ferradosa *et al.* (2018a, 2019a) pointed out that:

- Scour protection thickness (t_s) and foundation dimensions, such as the monopile diameter (D_p), are not considered in the design prediction equation.
- Using fixed sub-areas often overlooks damage occurring in intersection zones between sub-areas.
- Protections with considerable damage in adjacent sub-areas can have the same S_{3D} as one with considerable damage but in spread sub-areas, Figure 1, thereby misleading the evaluation and/or prediction of protection stability.
- Static, dynamic, and failure conditions can occur for values outside of the reference limits.
- By assuming a reference sub-area of $4D_{n50}^2$ as proposed by den Boon *et al.* (2004), the S_{3D} has the physical meaning of armour layer thickness reduction equal to $n_s \cdot D_{n50}$, being n_s the number of layers as a function of the stone sizes.

Therefore, the failure limit of $S_{3D}=1.0$ is only representative of failure for single-layer scour protections with a $t_s=D_{n50}$ ($n_s=1$), often leading to conservative estimates for multi-layer protections.

- The S_{3D} was dependent on the alignment of the sub-areas with the direction of the hydrodynamic conditions.

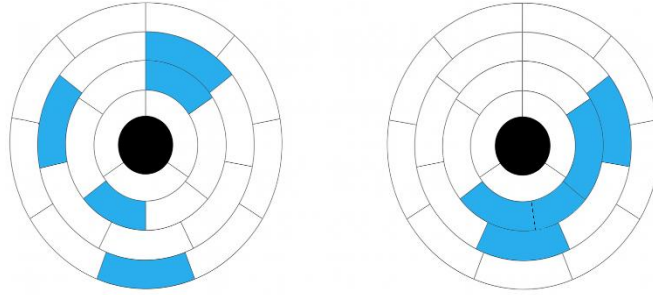


Figure 1: Different scour damage exposure for the same S_{3D} (blue areas): Left protection – Less prone to filter exposure (spread areas); Right protection – More prone to filter exposure (adjacent areas).

To address the limitations of De Vos *et al.*'s (2012) approach, Fazeres-Ferradosa *et al.* (2020) introduced a new methodology based on the damage assessment of overlapping sub-areas (Figure 2). This approach significantly improved damage characterisation by enabling a flexible element mesh to scan the scour protection and capture intersection zones. Moreover, it enabled a thorough statistical analysis to distinguish scour protections with the same maximum damage number ($S_{3D,max}$) but different erosion patterns. Different sub-areas, shapes, sizes, and overlapping distances were tested and compared. It was concluded that the overlapping distance had a reduced influence on the damage distribution. As for the sub-area shape, the circular sub-areas yielded the most accurate results in typical scenarios compared to ring-shaped sub-areas. Nonetheless, the grid ratio ($\eta_{S3D,grid}$), *i.e.*, resolution, Equation (2), and, therefore, the A_{sub} size, as shown in Equation (3), were found to be key elements in damage measurements ($S_{3Dsub,circle}$), Equation (4).

$$\eta_{3D,grid} = \frac{D_{n50}^2}{A_{sub}} \quad (2)$$

$$A_{sub} = \pi \cdot \left(\frac{n \cdot D_{n50}}{2} \right)^2 \quad (3)$$

$$S_{3Dsub,circle} = \frac{V_e}{D_{n50} \cdot A_{sub}^2} \quad (4)$$

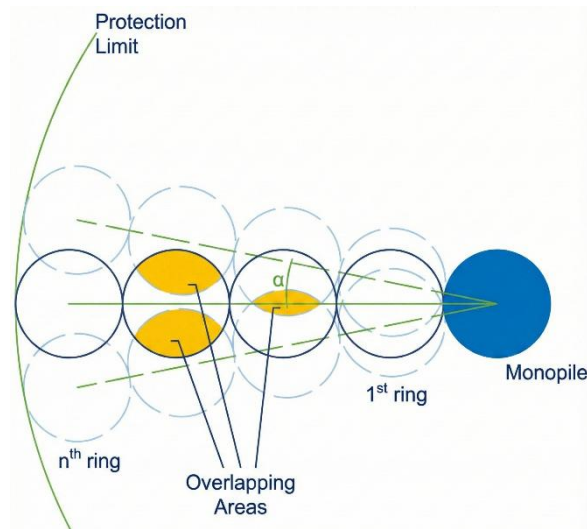


Figure 2: Scheme of the overlapping methodology concept proposed by Fazeres-Ferradosa *et al.* (2020).

Although Fazeres-Ferradosa *et al.* (2020) suggested that the methodology could be applied to foundations with different cross-sections, it was primarily developed and validated for monopiles with standard circular scour protection. Chambel *et al.* (2025) successfully applied it to a new set of physical model tests using a monopile and a hybrid (coupled with a wave energy converter) monopile foundation. Regarding the application to complex foundations, Chen *et al.* (2025b) applied the method to a 4-leg jacket. However, each leg was protected independently with a small circular scour protection, and the analysis performed treated each leg as a single monopile, rather than performing an overall analysis of the entire complex foundation.

Both cases successfully extended the experimental conditions used in Fazeres-Ferradosa *et al.* (2020), demonstrating the method's effectiveness. However, the method has not yet been fully applied to complex foundations protected by a single scour protection covering the entire structure's footprint. Additionally, uncertainty remains regarding the selection of sub-area size and, consequently, the grid ratio, as well as the definition of static and failure limits when applying this approach.

To address these issues, this study presents an improved framework that adapts and enhances the overlapping circle concept for a jacket foundation with a square scour protection of varying thickness, under combined wave and current conditions. By analysing the results of the experimental tests by Chambel *et al.* (2026), the improved method is shown to capture the damage distribution across the entire surface area of the protection, with particular focus on critical areas around the piles. Furthermore, to address concerns regarding the selection of the grid ratio and sub-area size, a detailed statistical analysis was conducted.

To assess global scour protection performance, this study introduces a novel approach that redefines failure based on spatial/volumetric loss rather than localised deformations. Nonetheless, for local scour damage characterisation, a new threshold calibration protocol is proposed to mitigate grid-related sensitivity. The primary objective of the protocol is to ensure that meshes with varying resolutions maintain the same diagnostic precision without generating false

positives. By integrating both global and local evaluation methodologies, this study aims to establish the adapted overlapping method as a robust, versatile tool applicable to a wide range of challenging offshore engineering scenarios.

The present work is structured as follows: Section 2 details the experimental setup, the methodological adaptation of the overlapping circle method for complex and non-standard geometry foundations, and a threshold calibration protocol. Section 3 presents the results of the statistical analysis, discusses the influence of mesh resolution, and introduces the dual framework for global and local scour evaluation. Finally, Section 4 summarises the main findings and conclusions regarding the applicability of the proposed methodology to a wider range of scour protections and offshore foundations.

2. Methodology

2.1 Experimental Setup and Hydrodynamic Conditions

The present research analysed data from the experimental tests conducted by Chambel *et al.* (2026). The physical model consisted of a 1:50 geometrically scaled jacket (Froude similitude) with square riprap scour protection of varying thickness, covering an area 1.25 times the jacket's footprint area (Figure 3). The scour protection was designed following the recommendations by Welzel *et al.* (2019), which suggests that the armour layer should be reinforced around the piles, and the thicknesses used on the reinforced areas ($5D_{n50}$) and the other adjacent areas ($3D_{n50}$) are within the scour depth range reported by Sarmiento *et al.* (2021).

The model was tested under combined waves and currents, as well as irregular and regular wave-only conditions. The experimental campaign also included a hybrid jacket foundation, in which a WEC was coupled to the structure. However, due to the extensive damage in those tests, the information provided would not help conduct a meaningful analysis for this research.

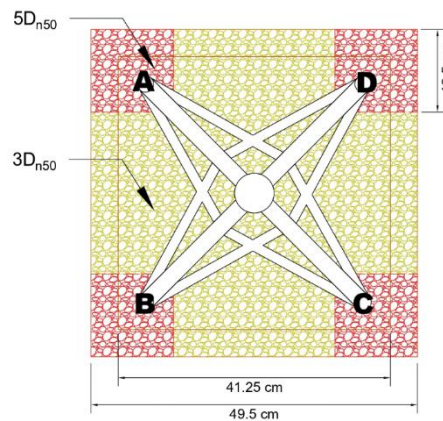


Figure 3: Experimental setup scheme and pile identification.

The bathymetry of the model was represented by 3D digital terrain models (DTMs) generated with a FARO® Focus Laser Scanner (2 million points/s, with 3D precision of 2mm at 10 m). The scanner enables measurements and the generation of high-resolution DTMs, providing an accurate portrayal of the eroded seabed and scour protection. Scans were conducted before, for each 1000-wave train, and after each test. The scanner's precision is smaller than the armour layer's D_{n50} , thus enabling the detection of small displacements and even punctual deformations. The DTMs' post-processing was carried out using Autodesk ReCap and CloudCompare to extract precise point clouds of the scour protection model, which were subsequently analysed using a MATLAB script that ran the adapted overlapping-circle method on the 4-leg jacket and the square-shaped scour protection to compute the measured S_{3D} values.

The hydrodynamic conditions (Table 1) used by Chambel *et al.* (2026) were selected to cover a range of different U_{cw} and KC values and were conducted up to 3000 waves. Three types of conditions were used for the jacket (J) tests: irregular waves combined with co-directional currents (WC), irregular waves only (WI), and regular waves only (WR). This allowed for the visualisation and analysis of different behaviours of the scour protections, which mostly ranged from stable to dynamic, and even close to failure.

Table 1: Experimental Hydrodynamic Conditions (Geometric Scale: 1:50).

Test	d [m]	H_s [m]	T_p [s]	U_c [m/s]	D_{85}/D_{15} [-]	D_{jacket}
J_WC_7	0.4	0.07	1.414	0.080	3	0.025
J_WC_11		0.11	1.697	0.143		
J_WC_15.5		0.155	1.980	0.183		
J_WI_14		0.14	2.263	0.208		
J_WR_14		0.14	2.263	0.208		

2.2 Adaptation of the Overlapping Scheme for Complex Geometries

The application of the overlapping method to a jacket foundation with non-standard square protection required an adaptation from the original approach developed for monopiles with standard circular protection. To address the geometric complexity of the setup, three discretisation strategies were considered to determine the optimal mesh configuration for assessing S_{3D} distribution. A 50% overlapping distance was selected for this research, as Fazeres-Ferradosa *et al.* (2020) found that no significant gains are obtained when using the method for distances other than the 50% selected value. The conceptual approaches are illustrated in Figure 4:

- Option #1 (Radial Approach): A direct adaptation of the original method, where the radial overlapping mesh is generated outward from the piles to the protection boundary. Each pile acts as a local origin – Figure 4 (left scheme).

- Option #2 (Trimmed Radial Approach): A modification of option A, where the elements deviating from the target 50% overlapping distance are removed to reduce redundancy – Figure 4 (middle scheme).
- Option #3 (Row-by-Row Approach): A linear, row-by-row discretisation strategy maintaining a constant 50% overlapping distance across the entire protection area – Figure 4 (right scheme).

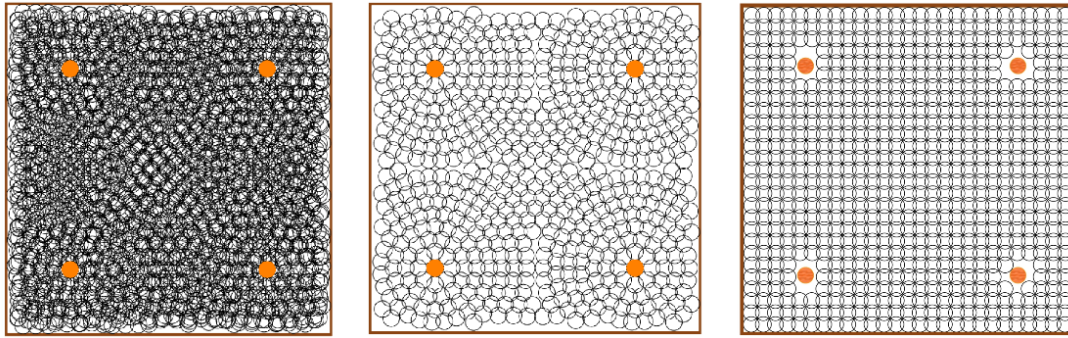


Figure 4: Illustration of overlapping method adaptation – Left scheme: Radial mesh arrangement (starting from the piles); Middle scheme: Radial mesh arrangement with removal of elements without correct overlapping distance; Right scheme: Row-by-row mesh arrangement (starting from the protection's edge).

Upon evaluating the generated meshes, option #1 was deemed unsuitable due to significant mesh redundancy and heterogeneity. Since the overall mesh is the result of multiple local meshes, each associated with a local sub-centre (jacket piles), the convergence of these grids leads to non-uniform overlapping distances, resulting in excessive computational noise and redundant calculations. Furthermore, this approach fails to account for the geometric boundaries of a square protection armour layer, resulting in insufficient coverage at the edges and vertices – critical zones where edge scour often initiates before propagating towards the piles.

Option #2 was an attempt to mitigate these issues by filtering out sub-areas that did not fully comply with the 50% overlapping distance requirement. While this reduced the number of sub-areas drastically, it still promoted spatial heterogeneity. As observed in Figure 4, this approach generates varying mesh densities, particularly along the central axes of the scour protection, creating localised gaps where damage distribution may be compromised. Consequently, this non-uniform distribution prevents a consistent analysis of the S_{3D} across the entire protection domain.

Ultimately, option #3 was selected as the final configuration. This row-by-row approach generates a uniform, consistent mesh that respects the defined overlapping distance globally rather than locally. It offers distinct advantages, such as:

- Complete coverage of the protection's boundaries (edge and vertices).
- Easier to program and apply.
- Significant reduction in computational cost.
- Homogeneous distribution of the sub-area elements.

Nonetheless, this arrangement also presents a minor disadvantage in covering the immediate vicinity of the jacket's piles. However, it was found that this can be effectively mitigated by increasing the grid ratio, *i.e.*, reducing the sub-area size, to refine the mesh resolution. To systematically assess the influence and accuracy of mesh selection, four different resolutions were used with increasing A_{sub} values, ranging from D_{n50}^2 to A_{pile_jacket} , corresponding to $\eta_{S3D,grid}$ decreasing from 1 to 2.78×10^{-2} (Figure 5). Therefore, option #3 was deemed the most robust, reliable, and computationally efficient framework for quantifying damage in complex foundation and non-standard protection geometries.

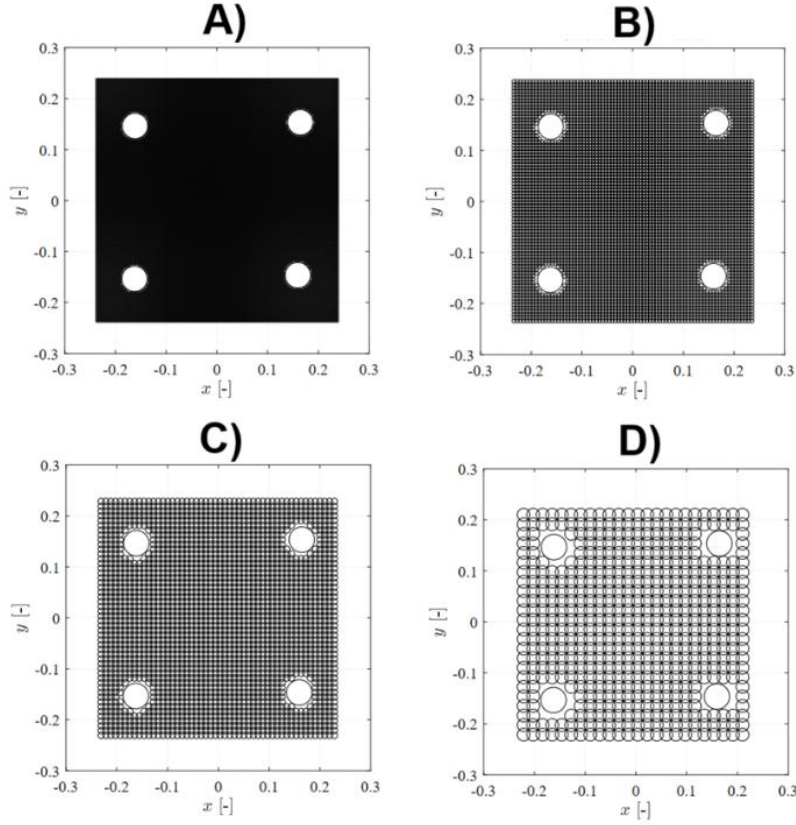


Figure 5: Row-by-row arrangement for different grid ratios and sub-areas: A) $\eta_{S3D,grid}=1$, $A_{sub}=D_{n50}^2$; B) $\eta_{S3D,grid}=1/4$, $A_{sub}=4D_{n50}^2$; C) $\eta_{S3D,grid}=1/9$, $A_{sub}=9D_{n50}^2$; D) $\eta_{S3D,grid}=2.78 \times 10^{-2}$, $A_{sub}=A_{pile_jacket}$.

2.3 Statistical Damage Characterisation

While $S_{3D,max}$ serves as the primary indicator of damage severity, relying solely on this metric may provide an incomplete history of the protection's state. In particular, $S_{3D,max}$ fails to capture the spatial distribution nuances of scour damage, leading to potential misperceptions when comparing protections with similar damage numbers that were exposed to different hydrodynamic conditions. Furthermore, in practical backfilling operations, the $S_{3D,max}$ does not provide a clear indication of where a larger quantity of material might be required. Figure 6 illustrates the cases of J_WC_15.5_3000 ($S_{3D,max}=4.71$) and J_WR_3000 ($S_{3D,max}=4.90$), where both protections yield nearly identical peak damage values, but display fundamentally different damage patterns.

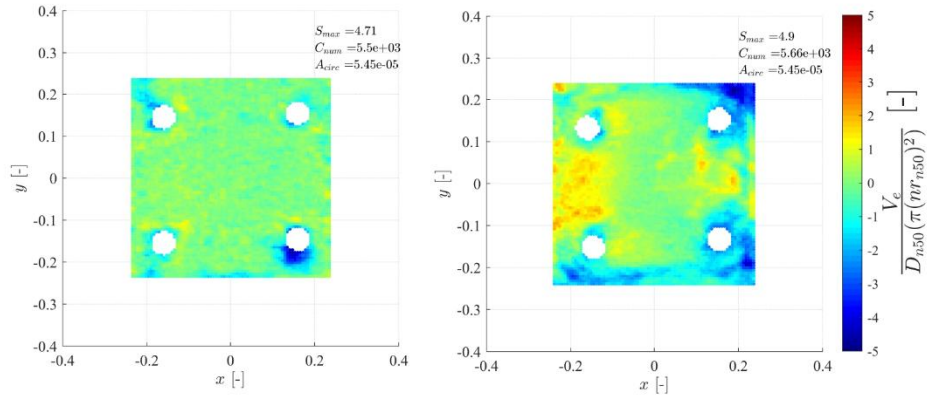


Figure 6: Damage pattern comparison: J_WC_15.5_3000 ($S_{3D,max}=4.71$) – left graphic; B) J_WR_14_3000 ($S_{3D,max}=4.90$) – right graphic.

To overcome some of the limitations mentioned and to provide a robust dataset for the subsequent sections, a comprehensive statistical damage analysis was conducted (see Tables 7-11 in the Appendix). The analysis focused on the reinforced scour protection areas adjacent to the jacket piles – regions identified as having the highest scour exposure and probability of failure. Using the newly adapted overlapping-circle method, four examined A_{sub} values were selected to span the four grid density ranges. The selection simplifies the derivation of the static and failure stability threshold limits while maintaining statistical rigour across the mesh density spectrum:

- Maximum Resolution ($\eta_{S3D,grid}=1$): maximum grid ratio, corresponding to an $A_{sub}=D_{n50}^2=1.36\times 10^{-5} \text{ m}^2$.
- Reference Resolution ($\eta_{S3D,grid}=1/4$): aligning with the reference area proposed by den Boon *et al.* (2004), corresponding to $A_{sub}=4D_{n50}^2=5.45\times 10^{-5} \text{ m}^2$.
- Intermediate Resolution ($\eta_{S3D,grid}=1/9$): provides a data point between the reference and minimum resolution, with an $A_{sub}=9D_{n50}^2=1.23\times 10^{-4} \text{ m}^2$.
- Minimum Resolution ($\eta_{S3D,grid}=2.78\times 10^{-2}$): the lowest grid ratio, corresponding to an $A_{sub}=A_{pile_jacket}=4.91\times 10^{-4} \text{ m}^2$.

For the selected A_{sub} , the following statistical metrics were computed to describe the damage distribution around Pile A through Pile D (Figure 3 and Table A.1 to Table A.5): $S_{3D,max}$, $S_{3D,mean}$, $S_{3D,min}$, Standard Deviation (σ_{S3D}), skewness, excessive kurtosis, and upper-bound percentiles – 99th Percentile (P_{99}), 95th Percentile (P_{95}), and 90th Percentile (P_{90}). Finally, the behaviour classification for each pile area was performed based on the results obtained and the visual assessment of the photographic register was collected during the experimental campaign.

2.4 Definition of Failure-Static Thresholds

As reported by Fazeres-Ferradosa *et al.* (2020), the selection of the grid ratio is a key component of the overlapping-circle method and can inherently affect the damage numbers. Moreover, the method's application to complex foundations and non-standard scour protection

geometries adds an additional degree of uncertainty regarding both the selection of the grid ratio and the static-failure threshold limits that describe each possible state of the scour protection (static, dynamic, or failure). To retain the diagnostic value of high- and low-resolution meshes without generating false positives for failure, a calibration procedure is proposed to determine and update the failure ($S_{3D,failure}$) and static ($S_{3D,static}$) thresholds based on $\eta_{S3D,grid}$ and A_{sub} selection.

The process should follow a five-step approach:

- Step 1 – Damage Classification and Ranking: each pile area should be classified and ranked based on the results from the S_{3D} value of the reference resolution supported by a visual assessment (Table A.6).
- Step 2 – Estimation of Failure Threshold: based on the subset of piles identified as “Dynamic (Close to Failure)”, the failure threshold estimation ($S_{3D,FTE}$) is obtained as the arithmetic mean of the damage numbers obtained for each resolution.
- Step 3 – Determination of Correction Factor (C_f): to account for minor deviations from the theoretical target, a correction factor (C_f) should be established, as the ratio between the failure threshold estimation ($S_{3D,FTE}$) and the theoretical threshold ($S_{3D,failure}=n_s$), for the reference scenario ($4D_{n50}^2$) – Equation (5).
- Step 4 – Failure Threshold Correction: for the non-reference resolutions, the final failure thresholds should be updated ($S_{3D,failure}=S_{3D,FTE}/C_f$) to consider mesh-related over- and underestimations.
- Step 5 – Estimation of Static Threshold: in the absence of a distinct reference for the static threshold for complex foundations and non-standard protection geometries, a static limit ($S_{3D,static}$) should be calibrated as the mean value using the data points identified as “Static (Close to Dynamic)”. A static threshold ratio (λ_{static}) is then computed as in Equation (6), for each individual resolution. The ratio quantifies the static-dynamic transition point as a normalised proportion of the failure threshold.

$$C_f = \frac{S_{3D,FTE}}{S_{3D,failure}} \quad (5)$$

$$\lambda_{static} = \frac{S_{3D,static}}{S_{3D,failure}} \quad (6)$$

Ideally, this calibration process should be validated against an extensive dataset covering a diverse range of hydrodynamic conditions and scour protection characteristics. This would allow for appropriate standardisation of both the static and failure thresholds across different mesh resolutions, thereby refining the S_{3D} ranges for distinct protection behaviours.

3. Results and Discussion

The new adaptation of the overlapping method was systematically applied to all experiments using a constant overlapping distance equal to 50% of the sub-area radius (R_{circle}). It is worth noting that the hybrid jacket test cases were excluded from this analysis, as the exhibited

catastrophic failure of the protection, characterised by extremely high S_{3D} values in those scenarios, to preserve the statistical integrity and prevent it from distorting the analysis's accuracy and relevance.

While the global analysis of the maximum damage number ($S_{3D,max}$), reported by Chambel *et al.* (2026), incorporates all the sub-areas analysed, the statistical analysis and the procedure recommended herein to define new static-failure threshold limits are discussed for the four representative resolutions shown in Figure 5.

3.1. Statistical Analysis

The $S_{3D,max}$ analysis performed by Chambel *et al.* (2026) pointed out a strong correlation between the maximum damage number and the intensity of the hydrodynamic conditions (J_WC_15.5, J_WI_14, and J_WR_14). For lower energy conditions, $S_{3D,max}$ values remained comparatively small. Figure 7 summarises the dependency between $S_{3D,max}$ and $\eta_{S3D,grid}$, revealing a positive correlation between both variables – aligned with the findings of Fazeres-Ferradosa *et al.* (2020). Thus, it can be generalised that the grid ratio selection needs to be carefully considered when determining the overall state of the scour protection, as it can yield a wide range of results that may lead to different interpretations.

Regarding the structural stability of the protections, all scour protections maintained their global integrity throughout the entire experimental campaign, encompassing all 3000 waves. However, distinct behavioural marks were assigned for each test: the J_WC_7 and J_WC_11 tests exhibited predominantly static behaviour, whereas the remaining tests were classified as dynamic. Nonetheless, under the J_WC_15.5 and J_WR_14 tests, the armour layer was close to reaching failure in the rear-pile region. A more comprehensive breakdown of the results can be found in Chambel *et al.* (2026).

By analysing the results presented in Table A.1-Table A.5, a distinct correlation is detected between the mesh resolution and the value of the maximum ($S_{3D,max}$) and minimum ($S_{3D,min}$) damage numbers. As the A_{sub} decreases – corresponding to a higher grid ratio and a finer mesh resolution – $S_{3D,max}$ and the absolute value of $S_{3D,min}$ (when negative represents sediment accretion) increase. Conversely, the $S_{3D,mean}$ at each pile location remains largely invariant, showing negligible sensitivity to variations in the grid ratio and the selected sub-area. Variations in the extreme values can be attributed to the behaviour of σ_{S3D} , which increases with increasing grid ratio. Therefore, the amplitude between the maximum and minimum values expands. Since the tighter mesh ($A_{sub}=D_{n50}^2$, $\eta_{S3D,grid}=1$) exhibits a higher standard deviation than the coarser resolution ($A_{sub}=A_{pile_jacket}$, $\eta_{S3D,grid}=2.78 \times 10^{-2}$), it generically yields higher absolute $S_{3D,max}$ and $S_{3D,min}$. Fundamentally, a coarser grid analysis reduces the frequency of outlier and extreme value occurrences by spatially averaging data, thereby smoothing the damage distribution.

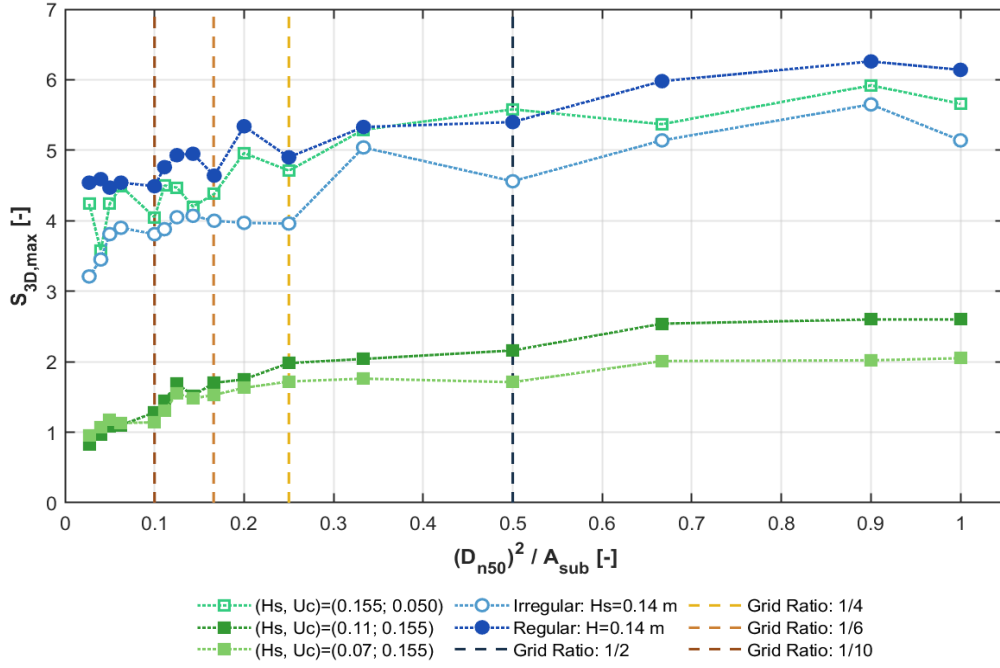


Figure 7: Variation of $S_{3D,max}$ with $\eta_{S3D,grid}$, Chambel *et al.* (2026).

The analysis of skewness and excess kurtosis shows that both values decrease as the grid ratio decreases, indicating a transition towards a more symmetrical distribution with values more evenly distributed around the mean, less intermittent, and with suppressed tail behaviour. This statistical smoothing makes the overlapping method with lower grid ratios particularly applicable to large- or prototype-scale monitoring, where the primary goal is to capture the macroscopic state of the protection, filtering out distribution noise rather than isolated spot deformations. By filtering these outliers, the analysis aligns more closely with decision-making information typically required in practical operations. Nevertheless, adopting larger meshes also entails a loss of potentially crucial information that must be carefully managed. The suppression of extreme values may mask specific damage spikes, making it necessary to investigate whether the lost data points correspond to transient spot deformations that the surrounding material can backfill or to future damaged zones that will require intervention due to significant erosion.

Overall, skewness values range from -1 to 1, indicating a slight positive tendency or a value close to zero. This trend represents a quasi-symmetric distribution with longer tails, reflecting the presence of outliers and extreme values on the damage (scour) side of the distribution. A notable deviation from this pattern was observed in the J_WC_11 test, where significant spatial asymmetry emerged between opposing structural features. Piles A and D exhibited a marked positive skewness around 2 (higher erosion than accretion), whereas piles B displayed a pronounced negative skewness around -2 (higher accretion of sediments). The same pile, which registered the highest absolute skewness value, exhibited the highest variation between its extreme values, as the magnitude of accretion ($|S_{3D,min}|=3.7$) substantially exceeded the maximum erosion ($S_{3D,max}=1.62$) at the highest grid resolution.

When trying to evaluate the statistical properties and the damage distribution symmetry characteristics for each stability regime, the following skewness values were identified (Figure 8):

- **Static Areas:** skewness $\in]-0.5, 0.5[$;
- **Static (Close to Dynamic) Areas:** skewness $\in]0, 1[$;
- **Dynamic Areas:** skewness ≈ 0
- **Dynamic (Close to Failure) Areas:** skewness ≈ 1 .

Interpreting the skewness correlations according to Bulmer's (1979) framework revealed that static and dynamic areas yield approximately symmetric distributions. Conversely, transitional states, particularly those areas near failure, are characterised by moderate to high skewness. Overall, the results suggest that physically, local scour manifests as an intermittent process, characterised by sharper deformations in localised areas or the occurrence of intense spot deformations. In contrast, sediment accretion and global scour tend to be spatially smoother.

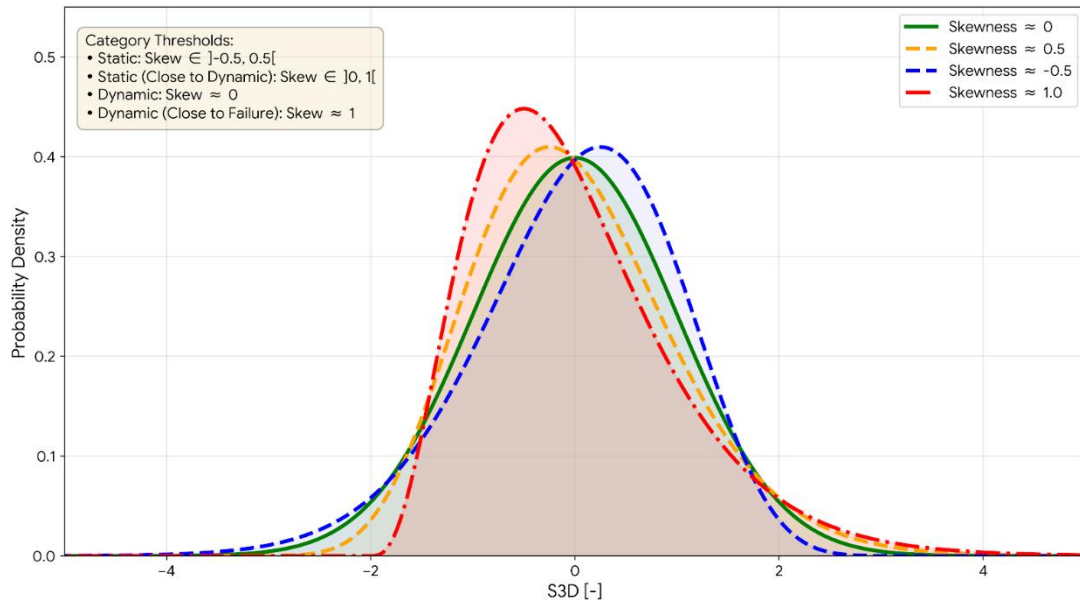


Figure 8: Representation of skewness for different scour protection stability regimes.

Regarding the excess kurtosis, most of the data fall within the range -1 and 1. Generally, the damage distribution is leptokurtic (positive kurtosis) at higher mesh resolutions, characterised by a sharper peak and heavier tails. It transitions to a platykurtic distribution (characterised by negative kurtosis) as the grid ratio decreases. This transition confirms that the damage distribution shows a distinct mesh-dependent tail behaviour. The positive kurtosis associated with a high-resolution mesh indicates that extreme values occur more frequently than predicted by a normal distribution, corresponding to a higher occurrence of localised severe scour sub-areas or intense accretion points that would not stand out. On the other hand, when a looser mesh is employed, these extreme values are attenuated by spatial averaging, resulting in a smoother distribution.

A significant deviation was once again noted for the J_WC_11 test, with high excess kurtosis values recorded: exceeding 10 for Pile B and 5 for Pile D. These high values coincided with the

areas of maximum modifications in the scour protection; Pile B exhibited the highest sediment accretion. In contrast, the maximum damage number was detected near Pile D's area. However, at the lowest grid ratio, kurtosis decreased significantly, effectively reducing the statistical significance of these local extremes.

When comparing the absolute maximum damage number with higher-order percentiles, such as the P_{99} , P_{95} , and P_{90} , a significant difference was observed, particularly for high grid ratios (Figure 9). In numerous instances, the P_{90} and P_{95} values were observed to be more than 1 unit lower than $S_{3D,max}$, and in other cases represented less than half of the maximum value.

The differences highlight that $S_{3D,max}$ is often governed by grid-scale selection and isolated outliers/extreme values originating in very localised areas. Therefore, it highlights that the absolute maximum damage number may be a statistically rare and non-representative value for the global state of scour protection, representing instead very specific local deformations. Relying solely on the $S_{3D,max}$ for design and decision-making purposes could therefore yield overly conservative criteria for dynamic protections. However, from a structural safety perspective, these local maximum values should not be disregarded, as evidenced by near-failure areas (Pile C in J_WC_15.5 and Piles C-D in J_WR_14), where the damage number values were close to the maximum, even for low grid ratios.

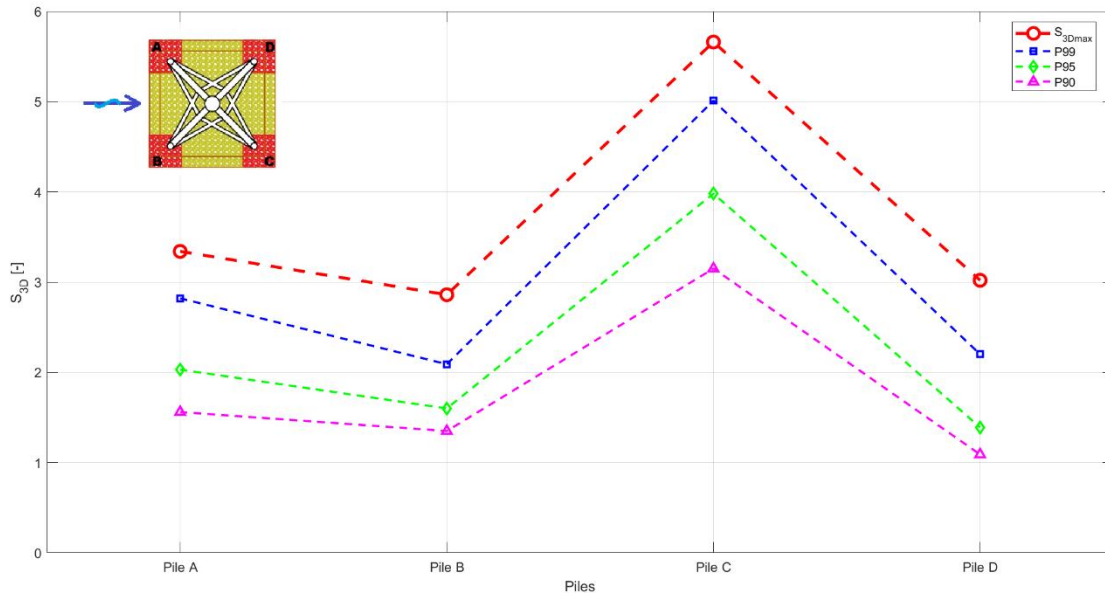


Figure 9: Comparison of $S_{3D,max}$ vs high-order percentiles for the highest grid ratio (J_WC_15.5 test).

As the mesh resolution is reduced, approaching $A_{sub}=A_{pile_jacket}$, the difference decreases: $S_{3D,max}$ decreases, and converges toward the P_{99} and P_{95} thresholds (Figure 10). For $A_{sub}=9D_{n50}^2$, the approximations only occur for the P_{99} . In the static test conditions and areas, even the P_{90} approaches the maximum (see Piles A-C-D J_WC_7 and Pile B-D in J_WC_11). This convergence implies that looser meshes effectively reduce the occurrence of extreme values and outliers, creating a more compact and statistically stable distribution of the damage. Nonetheless,

this stability comes at the cost of neglecting critical peak scour depths, potentially underestimating the potential severity of the cumulative damage effects.

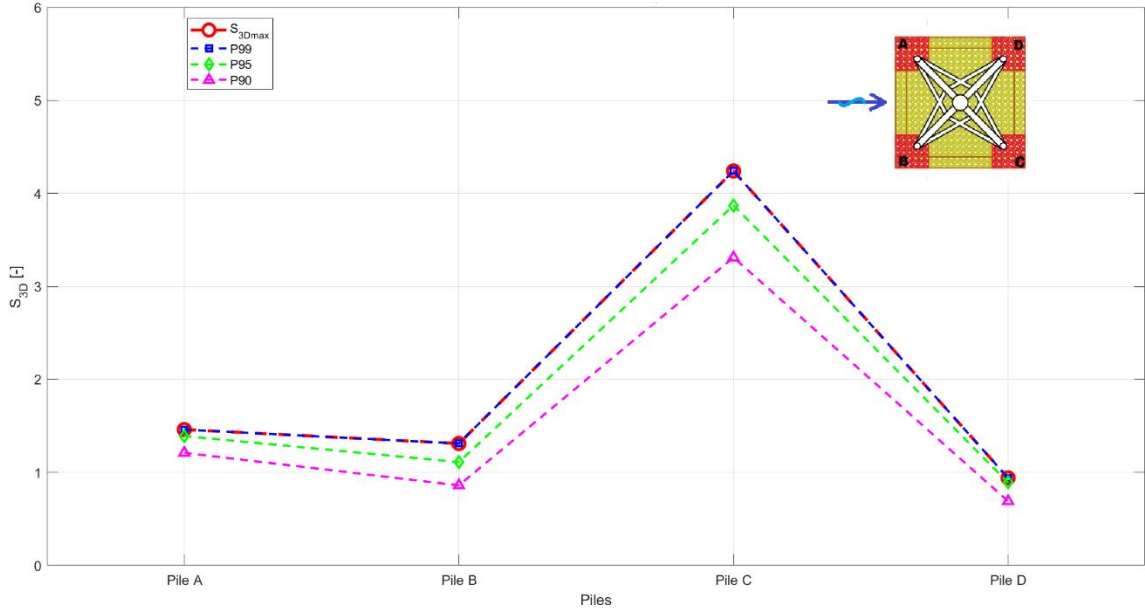


Figure 10: Comparison of $S_{3D,max}$ vs high-order percentiles for the lowest grid ratio (J_WC_15.5 test).

Focusing on the reference resolution ($A_{sub}=4D_{n50}^2$) proposed by den Boon *et al.* (2004), the statistical analysis indicates that while P_{99} occasionally aligns with the $S_{3D,max}$ for the most critical areas when damage is high, replacing $S_{3D,max}$ with the 99th percentile metric, at this resolution, is not justifiable for design and/or decision-making purposes. The trade-off of using P_{99} does not provide sufficient optimisation or a safety margin.

In summary, the assumptions underlying the statistical analysis suggest that the damage distribution exhibits intermittent, deep local deformation holes superimposed on a more spatially distributed erosion and accretion. The sensitivity analysis for the grid ratio shows that increasing mesh refinement amplifies both skewness and excess kurtosis, thereby improving the accuracy and resolution of extreme damage values and locations, respectively. However, the difference between $S_{3D,max}$ and the high-order percentiles in high-resolution grid meshes suggests that grid-scale singularities dominate the maximum and may lack statistical robustness. On the contrary, coarser meshes act as spatial filters that suppress tail behaviour, yielding compact, light-tailed distributions in which high percentiles converge toward $S_{3D,max}$. Thus, percentile-based metrics, such as P_{99} or P_{95} , could provide a more reliable and mesh-robust framework for interpreting the global state of scour protection, rather than searching for and discussing the effects of spot deformations. However, it is important to note that coarser meshes may or fail to detect the initial occurrence of winnowing – the loss of sediment through the scour protection (Wörman 1989; De Sonnevile *et al.*, 2014; Riezebos *et al.*, 2016; Schendel and Schlurmann, 2019). This morphological process can trigger a local failure that could lead to progressive loss of structural integrity, even if the global volume of protection is not significantly affected.

A critical evaluation of the spatial scale reveals the limitations of standard failure criteria. The sub-areas used in the adapted overlapping-circle method constitute only a fraction of the total scour protection area (Table 2).

These observations raise a fundamental question: Can the structural failure of a scour protection system be reliably inferred solely from highly localised damage affecting a residual percentage of the overall domain, or should it be evaluated from both a global and local perspective? The statistical evidence suggests that considering only local deformations may be methodologically limited, but the possibility of missing local failure mechanisms cannot be ruled out. Therefore, a joint global-local analysis should be considered to avoid the shortcomings of either approach.

Table 2: Quantification of the spatial scale of damage analysis against scour protection footprint (prototype values).

A_{sub}	Value [m ²]	$A_{sub}/A_{protection}$ (%)
D_{n50}^2	3.42×10^{-2}	0.006
$4D_{n50}^2$	1.37×10^{-1}	0.022
$9D_{n50}^2$	3.07×10^{-2}	0.050
A_{pile_jacket}	1.23	0.201
$A_{protection}$	612.56	
D_{n50} [m]	0.185	

The distinction is clearly described by the statistical tendencies observed:

- **High Grid Ratios (Micro-Scale):** characterised by higher skewness, positive kurtosis, and $S_{3D,max} \gg [P_{90}-P_{99}]$, indicating that extreme damage may be highly localised, representing spot deformations rather than global failure.
- **Low Grid Ratios (Macro-Scale):** characterised by lower skewness, negative kurtosis, and $S_{3D,max} \approx [P_{95}-P_{99}]$, indicating a more distributed damage response relevant to the overall integrity of the protection.

Hence, while high-resolution analysis is essential for understanding scour initiation and detecting local failure mechanisms, global failure criteria should better align with scales that reflect the overall structural performance of the scour protection armour layer. This means that extremely serious damage may be highly localised, but failure should also be assessed globally.

While high-resolution meshes can help capture worst-case scenarios and identify potentially dangerous scour initiation zones, they are often too sensitive for assessing global integrity. At such fine scales, extreme damage values may be statistically rare and over-represent damage, potentially conflating spot deformations with the overall stability of the protection system, which is essential for establishing real-life decision-making criteria.

Instead, structural performance should also be assessed at a spatial scale consistent with an acceptable fraction of the material loss after a specific hazard event. This implies a paradigm shift

in which the failure criterion is first defined in terms of allowable surface or volumetric loss (e.g., 1%, 2%, 5%), followed by the selection of equivalent A_{sub} and $\eta_{S3D,grid}$ values for analysis, and then the overlapping-circle method is applied. Larger sub-areas, while associated with lower grid ratios and distribution smoothing, may provide a fair assessment of the global system-level behaviour. By using statistically robust, percentile-based metrics, this approach may complement stakeholder needs for informed decision-making.

Far from compromising model validity, the use of looser meshes shifts the inquiry from resolving discrete point deformations to evaluating the system's global integrity. For operational purposes, this process may not only be acceptable but advantageous, offering significant reductions in time and costs while being computationally less demanding. Hence, fine-resolution mesh analysis should be retained as a complementary diagnostic tool for identifying localised vulnerability areas. At the same time, system-level performance is evaluated using coarser, physically meaningful spatial scales aligned with predefined acceptable failure criteria.

3.2. Scour Protection Global Damage Evaluation: Spatial/Volumetric-Based Approach

Current design methodologies and failure assessment of scour protections rely on the $S_{3D,max}$ derived from fixed (De Vos *et al.*, 2012) or overlapping sub-areas (Fazeres-Ferradosa *et al.*, 2020). Although reliability-based approaches have been introduced by Fazeres-Ferradosa *et al.* (2018b, 2019a, 2019b, 2019c) and validated with field data (Chambel *et al.*, 2022), critical limitations remain in the standard failure criteria.

Specifically, as De Vos *et al.* (2012) define S_{3D} as a reduction in armour layer thickness proportional to $n_s \cdot D_{n50}$, the standard failure threshold of $S_{3D,failure}=1.0$ is strictly valid for single-layer protections, *i.e.*, $t_s=D_{n50}$. This raises concerns regarding the conservatism of thicker armour layers, which can inherently withstand larger damage magnitudes without failure. Additionally, as demonstrated in the preceding statistical analysis, the overlapping method exhibits high sensitivity to mesh resolution (grid ratio selection), which may capture point deformations rather than provide a more comprehensive picture of the protection's structural instability. To address the global structural evaluation of scour protections, an alternative spatial/volumetric-based framework is proposed when applying the overlapping method:

- 1st stage: define an acceptable spatial/volume loss ($A_{L\%}$ or $V_{L\%}$) of armour layer material.
- 2nd stage: determine $A_{sub} = A_{protection} \times 1\%$, $\eta_{S3D,grid}$, and define $S_{3D,failure}=n_s$.
- 3rd stage: run the overlapping-circle method.

If any single sub-area yields a single $S_{3D,failure}$ value, the protection is deemed as failure, since the sub-area was deliberately scaled to detect exactly where a certain percentage of the total volume (V_T) was eroded entirely. The filter layer is completely exposed ($V_e=V_T \times V_{L\%}=A_{sub} \times S_{3D,failure}$), thus aligning with the protection's global structural requirements.

As a proof of concept, two $V_{L\%}$ values (0.5% and 1%) were selected to demonstrate this approach using the results from the surrounding area closer to Pile D in the J_WR_14 test, one

of the areas deemed close to failure. Figure 11 illustrates the results and comparison of a scale analysis derived for different $A_{\text{protection}}$, using the two selected $V_L\%$ values. When comparing the spatial/volumetric-based scale results with material-based resolutions, a notable contrast is observed. For the high-resolution meshes, $S_{3D,\text{max}}$ ranges from 6.14 to 4.54, which should imply failure, filter exposure, or severe damage.

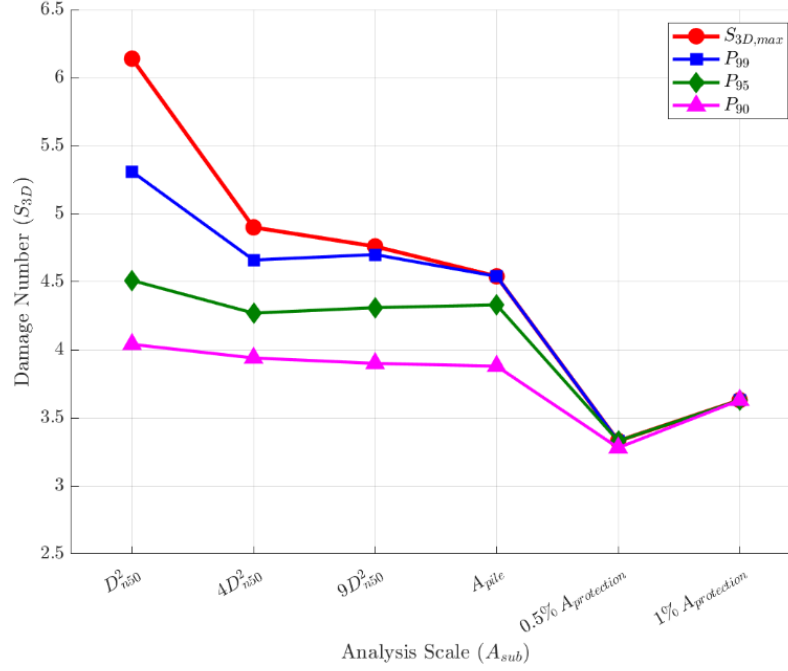


Figure 11: Evolution of damage vs mesh resolution: J_WR_14 test (Pile D).

Conversely, when A_{sub} was adjusted to represent volumetric losses of 0.5% and 1%, the damage number decreased significantly to 3.3-3.6. At these scales, $S_{3D,\text{max}}$ converges almost perfectly with the upper-bound percentiles, demonstrating the influence of grid selection on filtering some scattering. Moreover, visual inspections of the physical model (Figure 12) revealed no apparent filter exposure, and the scour protection appears to have retained its overall integrity, which is more consistent with the volumetric loss adjustment results and indicates a fairly dynamic profile. This discrepancy suggests that the high damage numbers for the initially selected resolutions may have been influenced by point deformations or local stone reorientations rather than structural collapse.

It is important to note that for the specific protection geometry, the value $V_L\%=1\%$ represented the practical upper limit for discretisation. Since A_{sub} depends on the total protection area, rather than an arrangement of armour layer units, increasing the $V_L\%$ in this specific case above 1% would result in a sub-area too large to fit consistently within the protection boundaries without missing sub-area elements, *i.e.*, without losing data points. Therefore, for the setup used by Chambel *et al.* (2026), the 0.5%-1% range provides a limit between robust statistical damage characterisation and geometric feasibility.



Figure 12: Pile D (J_WR_14 test).

3.3 Scour Protection Local Damage Evaluation

While the proposed spatial/volumetric framework assesses the global stability of protection, the four initial mesh resolutions remain indispensable tools for measuring local phenomena. The fine-scale analysis can capture scour with high precision in critical areas near the piles, helping identify potential worst-case scenarios and detect locations that could serve as precursors to failure. Despite understanding that scour also requires this level of precision, as demonstrated, the selected grid ratio can inherently inflate the resulting damage numbers. Therefore, the procedure described in Section 2.4 was applied using the dataset from the statistical analysis to retain the diagnostic value of using high- and low-resolution meshes.

3.3.1. Failure Threshold Estimation

The first step consisted of ranking the pile areas based on the $S_{3D,max}$ and visual assessment (see **Erro! A origem da referência não foi encontrada.** in the Appendix). Based on this ranking system, the failure limit estimations (Step 2) were calculated as the arithmetic mean value for the “Dynamic (Close to failure)” classification. Using data points from dynamic areas approaching failure aims to establish a threshold representative of this near-critical state, providing a reliable proxy for the actual threshold. Step 3 involved determining the correction factor to account for minor deviations from the theoretical target. The C_f value was obtained for the reference resolution and applied to the results obtained for all the remaining grid resolutions (resulting in Step 4). Table 3 summarises the obtained results from Steps 2 through 4, from which it can be concluded that:

- For the reference resolution ($A_{sub}=4D_{n50}^2$), the experimental mean damage number for the near-failure condition was established at $S_{3D,FTE}=4.73$. To align this baseline with the reference failure limit (assumed as $S_{3D,failure}=5.0$ for this specific protection setup), Step 3 resulted in a C_f of 0.945.
- For the highest mesh resolution ($A_{sub}=D_{n50}^2$), a. $S_{3D,FTE}=5.87$ is estimated first. After applying the C_f , the failure limit is adjusted to $S_{3D,failure}\approx 6.21$, representing an increase

of approximately 24% relative to the reference resolution limit. Therefore, when using the overlapping method, the threshold limit should be adjusted to account for mesh overestimation.

- On the opposite side, for the lowest mesh resolution ($A_{sub}=A_{pile_jacket}$), a $S_{3D,FTE}=4.23$ is estimated first, which, after correction, increases to $S_{3D,failure}=4.48$, representing a 10% decrease relative to the reference resolution failure limit, reflecting the attenuation of peak damage values. Therefore, when using the overlapping method, the threshold limit should be adjusted to account for mesh underestimation.

The calibration values obtained are preliminary and subject to refinement and consolidation through a more diverse set of experimental validations.

Table 3: Procedure to determine $S_{3D,failure}$ for different A_{sub} .

Classification: Dynamic (Close to Failure)			Threshold Limit
A_{sub}	$S_{3D,max}$		
D_{n50}^2	Max Value	6.14	Correction with C_f
	Min Value	5.46	
	Mean Value	5.87	
	$S_{3D,FTE}=5.87$		$S_{3D,failure}=6.21$
$4D_{n50}^2$	Max Value	4.90	Theoretical Reference: ($S_{3D,failure}=n_s$)
	Min Value	4.57	
	Mean Value	4.73	
	$S_{3D,FTE}=4.73$		$S_{3D,failure}=5.00$
$9D_{n50}^2$	Max Value	4.76	Correction with C_f
	Min Value	4.42	
	Mean Value	4.56	
	$S_{3D,FTE}=4.56$		$S_{3D,failure}=4.82$
A_{pile_jacket}	Max Value	4.54	Correction with C_f
	Min Value	3.92	
	Mean Value	4.23	
	$S_{3D,FTE}=4.23$		$S_{3D,failure}=4.48$

3.3.2. Static Threshold Estimation

The estimation of the static limit was focused on the subset “Static (Close to Dynamic)”. Table 4 presents a summary the data values associated with $S_{3D,static}$ while Table 5 shows the λ_{static} results that were obtained across the different mesh resolutions.

For the reference resolution ($A_{sub}=4D_{n50}^2$), the mean static threshold was set at 2.33, providing a benchmark for understanding how grid resolution affects the perception of static behaviour. Since no reference static limit was available, no C_f was applied to any of the metrics obtained. For each resolution, λ_{static} was determined as the ratio between the $S_{3D,static}$ and the corrected $S_{3D,failure}$. This formulation normalises the static limit relative to the failure limit, ensuring that λ_{static} represents a fraction of the failure criteria at any given resolution.

- For the highest mesh resolution ($A_{sub}=D_{n50}^2$), $S_{3D,static}$ value increased to 3.01, suggesting that a higher threshold is necessary to avoid misclassifying stable elements as dynamic, due to the mesh's high sensitivity to point deformations.

Although $\lambda_{static}=0.48$ appears elevated relative to the respective failure threshold, a wider margin for the dynamic zone was observed, compensating for the capture of point deformations, which require a higher normalised threshold.

- Conversely, for $A_{sub}=A_{pile_jacket}$, the static damage number limit dropped to 1.22, effectively filtering out outliers and extreme values, yielding a value that better represents the limited mobility of an armour layer composed of 5 layers of riprap material. The λ_{static} drops to 0.27, confirming that spatial averaging effectively filters out high local variations. At this resolution, the static level is significantly lower relative to the failure limit, reinforcing the expected representation for a motionless state.
- When analysing the complete set of λ_{static} values, for three of the four resolutions, consistent values were obtained, ranging between 0.44 and 0.48. These results suggest that, at a local scale, the transition from a static to a dynamic behaviour may occur approximately at the midpoint, around 0.45 of the failure threshold. For the A_{pile_jacket} sub-area, the ratio drops to 0.27. This reduction could result from using a larger analysis sub-area, which captures not only localised erosion peaks but also significant sediment accretion zones.
- The λ_{static} reduction may indicate that the A_{pile_jacket} resolution can be in a transition phase where it filters out point deformations, and it starts to trend towards a global analysis rather than to the local survey capability of finer meshes.

The values presented should be interpreted as indicative proposals that require the consolidation with a broader experimental dataset.

Table 4: Procedure to determine $S_{3D,static}$ for different A_{sub} .

Classification: Static (Close to Dynamic)		
A_{sub}	$S_{3D,max}$	
D_{n50}^2	Max Value	3.34
	Min Value	2.81
	Mean Value	3.01
$S_{3D,static}$		3.01
$4D_{n50}^2$	Max Value	2.05
	Min Value	2.59
	Mean Value	2.33
$S_{3D,static}$		2.33
$9D_{n50}^2$	Max Value	1.79
	Min Value	2.65
	Mean Value	2.11
$S_{3D,static}$		2.11
A_{pile_jacket}	Max Value	0.94
	Min Value	1.46
	Mean Value	1.22
$S_{3D,static}$		1.22

Table 5: λ_{static} values for each respective A_{sub} .

Classification: Static (Close to Dynamic)	
A_{sub}	λ_{static}
D_{n50^2}	0.48
$4D_{n50^2}$	0.47
$9D_{n50^2}$	0.44
A_{pile_jacket}	0.27

3.3.3. Limit Confirmation

After estimating static and failure thresholds for the four resolution meshes, these limits were compared with the $S_{3D,max}$ values from each test. This comparison aimed to verify if the damage classification attributed to each test remained consistent across all resolutions when using the respective thresholds for each grid.

Table 6 shows that the static tests (J_WC_7 and J_WC_11) consistently report maximum damage numbers below the static threshold across all resolutions, effectively categorising them as static, regardless of the grid ratio used. On the other hand, the remaining tests return values that exceed the static limit but remain below the failure threshold, except the J_WR_14 test, which, for the coarser resolution, triggers a failure event by exceeding the S_{3D} .

Table 6: Comparison of $S_{3D,max}$ location with threshold limits obtained.

$S_{3D,max}$ vs Thresholds					
A_{sub}	Damage Classification (Overall)	D_{n50^2}	$4D_{n50^2}$	$9D_{n50^2}$	A_{pile_jacket}
$S_{3D,static}$		3.01	2.33	2.11	1.22
$S_{3D,failure}$		6.21	5.00	4.82	4.48
J_WC_7	Static	2.05 (Pile B)	1.72 (Pile D)	1.30 (Pile D)	0.95 (Pile D)
J_WC_11	Static	2.62 (Pile D)	1.98 (Pile D)	1.45 (Pile D)	0.87 (Pile A)
J_WC_15.5	Dynamic (Close to Failure)	5.66 (Pile C)	4.71 (Pile C)	4.50 (Pile C)	4.24 (Pile C)
J_WI_14	Dynamic	5.14 (Pile B)	3.96 (Pile B)	3.88 (Pile B)	3.21 (Pile B)
J_WR_14	Dynamic (Close to Failure)	6.14 (Pile D)	4.90 (Pile D)	4.76 (Pile D)	4.54 (Pile D)

Regarding the spatial location of the $S_{3D,max}$ value, Table 6 provides critical insights. For the tests exceeding the static threshold (J_WC_15.5, J_WR_14, and J_WI_14), the location of peak damage remains at the same pile area across all resolutions. As reported by Zhang *et al.* (2024), these high damage tests were associated with higher wave heights and longer peak wave periods. In contrast, the static tests exhibit some instability, particularly with the most affected pile. For the J_WC_7 test, the $S_{3D,max}$ shifts from pile B in the tighter mesh to pile D, in the remaining meshes. As for the J_WC_11 test, the opposite occurs: the $S_{3D,max}$ shifts from pile A in the lowest-

resolution mesh to pile D in the remaining resolutions. This variation in low-damage scenarios may suggest that, for static configurations in which the armour layer unit movement is residual when the armour layer material moves slightly, the maximum damage value is driven by minor reorientations.

It is essential to highlight that the analysis and results presented in Section 3.3 serve as a proof of concept for the calibration procedure proposed in Section 2.4, utilising the limited dataset currently available. To refine and validate the procedure, extensive experimental testing is necessary to:

- Establish how sensible results can be to a wider range of hydrodynamic conditions.
- To assess how different combinations of waves and/or current conditions can dictate damage patterns and establish the most prone damage locations.
- To verify whether the transition between static, dynamic, and failure behavioural stages, at both local and global scales, consistently occur at these specific fractions of the failure limit, or if they may vary significantly under broader hydrodynamic conditions.

Furthermore, future research should prioritise redundancy tests to ensure data reliability and to isolate whether the observed variations were systematic or stochastic.

4. Conclusions

This research presents a novel row-by-row overlapping method that extends the original concept (Fazeres-Ferradosa *et al.*, 2020) to complex foundations and non-standard scour-protection geometries. The influence of mesh resolutions on damage quantification and distribution was evaluated by comparing four distinct grid ratios and sub-areas. The analysis provided a method to adjust the static/dynamic/failure threshold limits based on the grid ratio used in the bathymetric profile analysis.

Through a thorough statistical analysis, an explicit dependency between mesh resolution and damage was observed. It was observed that the high-resolution mesh ($A_{sub}=D_{n50}^2$) provided the highest $S_{3D,max}$, driven by positive skewness and excess kurtosis, which indicates that these values may be representative of extremely high point deformations rather than global failure. Conversely, coarser resolutions ($A_{sub}=A_{pile_jacket}$) might filter out some data scatter, producing smoother distributions where upper-bound percentiles converge with the maximum values. This confirms that while high-resolution grids are sensitive to individual unit deformations, looser resolutions may be more effective in distinguishing between negligible deformations and critical structural failure.

To address the disparity between local and global scour damage, a different framework was proposed. The approach for global stability evaluation shifts the focus from residual exposure of the filter layer to a more meaningful spatial/volumetric loss percentage of the armour layer material. When applied to the experimental data, the method demonstrated that protections previously identified as being close to failure using the reference criteria ($A_{sub}=4D_{n50}^2$) of den Boon

et al. (2004) presented higher levels of structural integrity. More specifically, when applying the volumetric approach with a $V_L\%=1\%$, $S_{3D,max}$ decreased from 6.14 to 3.6 (for the J_WR_14 test), approximating the maximum value to the upper-bound percentiles, effectively filtering localised point deformations and providing a damage value that more closely aligns with visual observations. This suggests that defining failure based on a higher allowable volume of material loss might provide a more physically meaningful and feasible criterion for large-scale monitoring and decision-making.

Despite high-resolution meshes (smaller circles) providing overestimations of the damage number, they can remain a complementary tool for measuring local phenomena in research, capturing scour with high precision in critical areas closer to the piles, and helping detect potential locations that could serve as precursors to failure and for the design of worst-case scenarios. Therefore, a calibration protocol was proposed to adjust the static and failure thresholds based on the selected mesh resolution.

Based on the results, a correction factor was estimated and applied to the initial estimates of the failure threshold ($S_{3D,FTE}$) to maintain diagnostic precision independent of mesh resolution and avoid false positives. Hence, the final failure thresholds ($S_{3D,failure}$) were adjusted approximately by +24% ($A_{sub}=D_{n50}^2$) and by -10% ($A_{sub}=A_{pile_jacket}$), relative to the reference resolution ($A_{sub}=4D_{n50}^2$). Regarding the static threshold, the protocol proposes a static ratio (λ_{static}) that allows the quantification of the $S_{3D,static}$ as a percentage of the $S_{3D,failure}$, for each resolution. A ratio reduction, from 0.48 ($A_{sub}=D_{n50}^2$) to 0.27 ($A_{sub}=A_{pile_jacket}$), was quantified, showing once more the filtering effect of coarser resolutions.

By applying these calibrated thresholds, the study provided a protocol for retaining the diagnosis of scour protection behaviour independently of the selected mesh resolution. It must be emphasised that the quantitative thresholds derived in this study are preliminary proposals intended as a proof of concept and require further consolidation through extensive future testing to establish definitive values.

The successful adaptation and application of a dual-scale paradigm to assess local and global damage, using the overlapping-circle method for scour protection, ensures a post-process tool that facilitates proper evaluations to determine maintenance interventions in the field and survey analysis. These evaluations are driven by in-depth statistical analysis, enabling accurate assessment of structural failure from local deformations.

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Appendix

2

3

Table A.1: J_WC_7 statistical results.

<i>A_{sub}</i>	Front Piles								Rear Piles							
	Pile A				Pile B				Pile C				Pile D			
	<i>D_{n50}²</i>	<i>4D_{n50}²</i>	<i>9D_{n50}²</i>	<i>A_{pile jacket}</i>	<i>D_{n50}²</i>	<i>4D_{n50}²</i>	<i>9D_{n50}²</i>	<i>A_{pile jacket}</i>	<i>D_{n50}²</i>	<i>4D_{n50}²</i>	<i>9D_{n50}²</i>	<i>A_{pile jacket}</i>	<i>D_{n50}²</i>	<i>4D_{n50}²</i>	<i>9D_{n50}²</i>	<i>A_{pile jacket}</i>
<i>S_{3D,max}</i>	1.93	1.29	1.21	0.90	2.05	1.26	0.98	0.48	1.24	0.85	0.42	0.07	2.04	1.72	1.30	0.95
<i>S_{3D,min}</i>	-1.20	-0.69	-0.63	-0.23	-1.42	-0.93	-0.70	-0.44	-1.51	-1.23	-1.08	-0.65	-0.94	-0.54	-0.30	-0.04
<i>S_{3D,mean}</i>	0.49	0.49	0.51	0.52	0.08	0.06	0.08	0.06	-0.34	-0.34	-0.34	-0.29	0.39	0.40	0.41	0.40
<i>σ_{S3D}</i>	0.43	0.37	0.33	0.29	0.40	0.34	0.29	0.22	0.36	0.31	0.27	0.21	0.41	0.36	0.33	0.33
Skewness	-0.06	-0.33	-0.72	-0.92	0.65	0.39	0.33	-0.37	0.08	0.15	0.09	0.01	0.28	0.13	0.19	0.24
Kurtosis	0.55	0.21	1.17	0.47	2.07	0.98	0.64	-0.23	0.50	0.30	0.24	-0.99	0.83	0.28	-0.24	-1.30
<i>P₉₉</i>	1.48	1.25	1.15	0.90	1.20	1.09	0.95	0.48	0.50	0.36	0.39	0.07	1.47	1.27	1.27	0.95
<i>P₉₅</i>	1.19	1.09	1.01	0.89	0.80	0.59	0.54	0.40	0.24	0.15	0.09	0.03	1.07	1.00	0.92	0.92
<i>P₉₀</i>	1.05	0.94	0.91	0.83	0.57	0.49	0.46	0.28	0.09	0.06	0.01	-0.02	0.89	0.82	0.83	0.82
Classification	Static				Static				Static				Static			

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5

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Table A.2: J_WC_11 statistical results.

<i>A_{sub}</i>	Front Piles								Rear Piles							
	Pile A				Pile B				Pile C				Pile D			
	<i>D_{n50}²</i>	<i>4D_{n50}²</i>	<i>9D_{n50}²</i>	<i>A_{pile jacket}</i>	<i>D_{n50}²</i>	<i>4D_{n50}²</i>	<i>9D_{n50}²</i>	<i>A_{pile jacket}</i>	<i>D_{n50}²</i>	<i>4D_{n50}²</i>	<i>9D_{n50}²</i>	<i>A_{pile jacket}</i>	<i>D_{n50}²</i>	<i>4D_{n50}²</i>	<i>9D_{n50}²</i>	<i>A_{pile jacket}</i>
<i>S_{3D,max}</i>	1.91	1.51	1.18	0.82	1.62	1.14	1.16	0.45	1.78	1.21	1.09	0.57	2.62	1.98	1.45	0.23
<i>S_{3D,min}</i>	-0.90	-0.54	-0.48	-0.16	-3.73	-3.36	-1.52	-0.62	-1.68	-1.53	-1.23	-0.47	-0.90	-0.76	-0.45	-0.30
<i>S_{3D,mean}</i>	0.07	0.07	0.06	0.06	0.07	0.06	0.14	0.10	-0.06	-0.06	0.02	0.08	-0.01	-0.03	-0.03	-0.06
<i>σ_{S3D}</i>	0.36	0.31	0.27	0.21	0.57	0.55	0.33	0.24	0.45	0.40	0.37	0.21	0.45	0.39	0.35	0.19
Skewness	1.07	1.41	1.72	2.42	-2.57	-3.09	-1.23	-1.24	-0.31	-0.36	-0.64	-0.24	1.82	2.15	2.42	0.38
Kurtosis	2.35	3.18	4.62	6.41	12.15	14.00	6.84	2.16	0.72	0.64	1.30	1.66	5.48	6.61	6.67	-1.16
<i>P₉₉</i>	1.28	1.14	1.16	0.82	1.19	1.03	0.98	0.45	1.00	0.95	0.81	0.57	1.76	1.67	1.36	0.23
<i>P₉₅</i>	0.80	0.74	0.56	0.52	0.74	0.66	0.64	0.41	0.59	0.51	0.44	0.46	0.81	0.67	0.65	0.23
<i>P₉₀</i>	0.50	0.39	0.40	0.25	0.57	0.52	0.54	0.39	0.44	0.35	0.35	0.30	0.47	0.39	0.34	0.22
Classification	Static				Static				Static				Static			

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Table A.3: J_WC_15.5 statistical results.

	Front Piles								Rear Piles							
	Pile A				Pile B				Pile C				Pile D			
A_{sub}	D_{n50^2}	$4D_{n50^2}$	$9D_{n50^2}$	A_{pile_jacket}	D_{n50^2}	$4D_{n50^2}$	$9D_{n50^2}$	A_{pile_jacket}	D_{n50^2}	$4D_{n50^2}$	$9D_{n50^2}$	A_{pile_jacket}	D_{n50^2}	$4D_{n50^2}$	$9D_{n50^2}$	A_{pile_jacket}
$S_{3D,max}$	3.34	2.50	2.65	1.46	2.86	2.05	1.88	1.31	5.66	4.71	4.50	4.24	3.02	2.59	2.10	0.94
$S_{3D,min}$	-1.31	-0.91	-0.79	-0.54	-1.09	-0.74	-0.52	-0.30	-0.97	-0.76	-0.60	0.01	-0.87	-0.65	-0.57	0.01
$S_{3D,mean}$	0.53	0.49	0.52	0.44	0.45	0.40	0.42	0.33	1.10	1.09	1.12	1.48	0.41	0.39	0.37	0.38
σ_{S3D}	0.78	0.71	0.68	0.66	0.63	0.57	0.51	0.40	1.35	1.26	1.22	1.27	0.53	0.47	0.41	0.26
Skewness	0.76	0.58	0.68	0.03	0.53	0.47	0.57	0.65	1.10	0.99	1.02	0.71	1.25	1.41	1.42	0.56
Kurtosis	0.48	-0.29	0.10	-1.11	0.00	-0.37	-0.18	-0.13	0.53	0.10	0.09	-0.66	2.84	3.46	3.85	-0.44
P_{99}	2.82	2.32	2.45	1.46	2.09	1.68	1.82	1.31	5.01	4.39	4.37	4.24	2.20	2.19	2.04	0.94
P_{95}	2.03	1.70	1.60	1.39	1.60	1.47	1.29	1.11	3.98	3.74	3.62	3.87	1.39	1.26	0.99	0.89
P_{90}	1.56	1.46	1.41	1.21	1.35	1.22	1.14	0.86	3.15	3.11	3.10	3.31	1.09	0.99	0.88	0.69
Classification	Static – Close to Dynamic				Static – Close to Dynamic				Dynamic – Close to Failure				Static – Close to Dynamic			

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Table A.4: J_WI_14 statistical results.

	Front Piles								Rear Piles							
	Pile A				Pile B				Pile C				Pile D			
A_{sub}	D_{n50^2}	$4D_{n50^2}$	$9D_{n50^2}$	A_{pile_jacket}	D_{n50^2}	$4D_{n50^2}$	$9D_{n50^2}$	A_{pile_jacket}	D_{n50^2}	$4D_{n50^2}$	$9D_{n50^2}$	A_{pile_jacket}	D_{n50^2}	$4D_{n50^2}$	$9D_{n50^2}$	A_{pile_jacket}
$S_{3D,max}$	4.35	3.39	3.07	2.84	5.14	3.96	3.88	3.21	5.00	3.31	3.31	2.82	3.86	3.21	2.61	1.96
$S_{3D,min}$	-0.65	-0.37	-0.04	0.12	-1.27	-0.91	-0.90	-0.50	-0.50	-0.40	-0.20	0.13	-0.37	-0.10	-0.04	0.19
$S_{3D,mean}$	1.53	1.52	1.54	1.37	1.06	1.05	1.05	1.04	1.56	1.54	1.58	1.57	1.23	1.24	1.21	1.19
σ_{S3D}	0.86	0.78	0.72	0.70	1.02	0.95	0.98	0.86	0.81	0.75	0.73	0.69	0.63	0.56	0.50	0.42
Skewness	0.36	-0.04	-0.07	0.05	0.27	-0.01	0.16	0.10	-0.08	-0.47	-0.51	0.39	0.46	0.35	-0.01	-0.39
Kurtosis	-0.21	-0.57	-0.75	-0.75	0.31	-0.19	0.00	-0.27	-0.13	-0.43	-0.24	-0.46	0.43	0.58	0.10	0.02
P_{99}	3.70	3.16	3.03	2.84	3.76	3.45	3.74	3.21	3.38	2.85	2.92	2.82	2.87	2.81	2.47	1.96
P_{95}	3.04	2.76	2.71	2.54	2.66	2.39	2.42	2.26	2.85	2.54	2.57	2.68	2.38	2.19	1.99	1.87
P_{90}	2.67	2.47	2.52	2.28	2.26	2.06	2.03	2.07	2.61	2.42	2.41	2.36	2.04	1.92	1.85	1.73
Classification	Dynamic				Dynamic				Dynamic				Dynamic			

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Table A.5: J_WR_14 statistical results.

<i>A_{sub}</i>	Front Piles								Rear Piles							
	Pile A				Pile B				Pile C				Pile D			
	<i>D_{n50}²</i>	<i>4D_{n50}²</i>	<i>9D_{n50}²</i>	<i>A_{pile_jacket}</i>	<i>D_{n50}²</i>	<i>4D_{n50}²</i>	<i>9D_{n50}²</i>	<i>A_{pile_jacket}</i>	<i>D_{n50}²</i>	<i>4D_{n50}²</i>	<i>9D_{n50}²</i>	<i>A_{pile_jacket}</i>	<i>D_{n50}²</i>	<i>4D_{n50}²</i>	<i>9D_{n50}²</i>	<i>A_{pile_jacket}</i>
<i>S_{3D,max}</i>	2.81	2.17	1.79	1.17	3.65	3.37	2.76	2.52	5.46	4.57	4.42	3.92	6.14	4.90	4.76	4.54
<i>S_{3D,min}</i>	-2.75	-2.09	-1.98	-1.31	-1.54	-1.21	-0.78	-0.44	-0.04	0.32	0.42	0.92	-0.04	0.17	0.15	0.85
<i>S_{3D,mean}</i>	0.03	0.04	0.06	0.05	1.02	1.01	1.02	1.08	1.88	1.90	1.88	1.92	2.43	2.43	2.33	2.51
<i>σ_{S3D}</i>	0.75	0.65	0.63	0.52	0.98	0.94	0.92	0.86	0.77	0.69	0.68	0.58	1.14	1.04	1.07	1.02
Skewness	0.05	0.04	0.07	-0.03	-0.002	-0.11	-0.07	-0.03	0.99	0.96	0.98	1.41	0.41	0.18	0.23	0.22
Kurtosis	1.47	1.09	1.12	0.73	-0.55	-0.74	-0.98	-1.14	2.02	1.99	2.02	3.03	-0.16	-0.61	-0.58	-0.79
<i>P₉₉</i>	2.01	1.64	1.65	1.17	3.13	2.88	2.70	2.52	4.56	4.31	4.22	3.92	5.31	4.66	4.70	4.54
<i>P₉₅</i>	1.34	1.20	1.14	0.97	2.59	2.40	2.50	2.31	3.21	3.20	3.21	2.81	4.51	4.27	4.31	4.33
<i>P₉₀</i>	0.98	0.91	0.96	0.79	2.31	2.19	2.19	2.23	2.85	2.66	2.55	2.66	4.04	3.94	3.90	3.88
Classification	Static – Close to Dynamic				Dynamic				Dynamic – Close to Failure				Dynamic – Close to Failure			

Table A.6: $S_{3D,max}$ vs scour protection behaviour classification.

Structure	Test	Pile	D_{n50}^2	$4D_{n50}^2$	$9D_{n50}^2$	$A_{pile\ jacket}$	Classification
Jacket	J_WC_7	A	1.93	1.29	1.21	0.90	Static
		B	2.05	1.26	0.98	0.48	
		C	1.24	0.85	0.42	0.07	
		D	2.04	1.72	1.30	0.95	
	J_WC_11	A	1.91	1.51	1.18	0.82	
		B	1.62	1.14	1.16	0.45	
		C	1.78	1.21	1.09	0.57	
		D	2.62	1.98	1.45	0.23	
	J_WR_14	A	2.81	2.17	1.79	1.17	Static (Close to Dynamic)
	J_WC_15.5	A	3.34	2.50	2.65	1.46	
		B	2.86	2.05	1.88	1.31	
		D	3.02	2.59	2.10	0.94	
	J_WI_14	A	4.35	3.39	3.07	2.84	Dynamic
		B	5.14	3.96	3.88	3.21	
		C	5.00	3.31	3.31	2.82	
		D	3.86	3.21	2.61	1.96	
	J_WR_14	B	3.65	3.37	2.76	2.52	Dynamic (Close to Failure)
	J_WR_14	C	5.46	4.57	4.42	3.92	
		D	6.14	4.90	4.76	4.54	
	J_WC_15.5	C	6.01	4.71	4.50	4.24	