SAND BYPASS STUDY
Aveiro Lagoon Mouth and Figueira da Foz River Mouth Case Studies

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Thesis submitted for the partial fulfilment of the requirements for the degree of
MASTER IN CIVIL ENGINEERING—SPECIALISATION IN HYDRAULICS

Supervisor: Full Professor Fernando Veloso Gomes

JUNE 2017
**Sand Bypass Study. Aveiro Lagoon Mouth and Figueira da Foz River Mouth Case Studies**

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**MESTRADO INTEGRADO EM ENGENHARIA CIVIL 2016/2017**

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Aos meus Pais e Irmão, à Mafalda, aos meus Primos, Família e Amigos

*A dream you dream alone is only a dream. A dream you dream together is reality.*

*John Lenon*
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ACKNOWLEDGEMENTS

My sincerest thanks go to my supervisor Professor Fernando Veloso Gomes, full professor at the Faculty of Engineering of the University of Porto (FEUP), for his support, the trust he placed in this theme, the constant advisory regarding every question I had and, mostly, for igniting my passion for Coastal Engineering through all his experiences in the field.

I would like to express my sincere gratitude to Aveiro and Figueira da Foz Port Authority for having welcomed me so well and provide all the data and support that was possible, especially Engineer Luís Godinho and Engineer Carla Garrido.

My thanks extend to all the entities that contributed to the unstoppable development of this thesis: Mr. Wayne Jansen from Transnet National Ports Authority, responsible for Port of Ngqura Sand Bypass System, Mr John Bendel, Project Manager (Infrastructure and Operations) of Nerang River Sand Bypass System, Mr Kim Bowra, Senior Coastal Management Specialist, and Kevin Filer, from McConnel Dowell Constructors, both from Tweed River Sand Bypass System, Clive Greyling, Civil Technologist from Durban Sand Bypass System and Dan Brower, from Shoreline & Waterway Management, responsible for Indian River Sand Bypass System.

I would also like to thank Ursula von Sain Ange and Sarel M. Hassbroek from CSIR who provided me wave data from Port of Ngqura and Port of Durban wave buoys.

To Hydraulics and Water Resources Institute (IHRH), particularly Ms. Esmeralda Miguel, I thank you for the tireless help in every issue that occurred.

I would like to thank my family and friends for all the support, the understanding, and the effort to compensate my absence.

To my parents and brother, thank you for always being there.

To my girlfriend Mafalda, who was an incredible help all the time and during all the circumstances.
ABSTRACT

The establishment of river inlets has been a usual practice for a number of centuries. In most cases the river inlet has been opened artificially. In order to maintain the opening, there was a need to build rubble mound breakwaters to limit sedimentation transport into the river inlet. However, while the breakwaters are effective at reducing the sedimentation transport into the river inlet, they cause an unwanted side effect. The breakwaters lead to an accretion of sediment updrift and an erosion of sediment downdrift of the breakwaters breaking the natural flow of sediment along the coastline.

The ‘Aveiro Lagoon Mouth’ and the ‘Figueira da Foz River Mouth’ together have influenced a length of the coastline longer than 200 km. This stretch of coastline has been suffering from an enormous accretion on the updrift side and even more enormous erosion downdrift. As a result, a permanent erosion mitigation solution seems to be extremely necessary due to the large amount of people and infrastructures that directly depend on this part of the coastline.

Even though there is no strict law or ruling requiring Port Authorities or river management entities to maintain the natural longshore sediment transport. These entities have realized the importance of natural sediment transport and how they affect it in a bad way, a subject studied during the last decades and continually published in specialized papers. There is also a published studied regarding a possible sand bypass system for Aveiro Lagoon Mouth, developed in 1960s.

The first part of this thesis is an exhaustive literature review to determine how river inlets and mouths are currently being treated around the world. While the second part focuses on the most appropriate solution for the two Portuguese cases.

KEYWORDS: Sand Bypass System, Artificial Beach Nourishment, Coastal Erosion, Aveiro Port, Figueira da Foz Port
RESUMO

O estabelecimento de embocaduras de rios é uma prática corrente desde há vários séculos. Na maior parte dos casos as embocaduras são abertas artificialmente. De maneira a manter a abertura, é necessária a construção de quebramares de taludes ou esporões para limitar a entrada de sedimentos nas embocaduras. No entanto, enquanto que os quebramares, ou os esporões, são bastantes eficazes a reduzir o movimento de sedimentos para a embocadura, têm um efeito secundário. Estas estruturas marítimas causam acreção de areias a barlamar e erosão de sedimentos a sotamar, causando uma barreira à deriva litoral.

Juntas, as embocaduras da Ria de Aveiro e a Foz do Rio da Figueira da Foz têm influência em mais de 200 km da costa portuguesa. Este comprimento de costa tem sofrido de uma enorme acreção a barlamar e ainda maior erosão a sotamar. Como resultado, medidas permanentes de alimentação artificial de praias, de modo a passar as areias de barlamar para sotamar, parecem ser extremamente necessárias devido ao elevadíssimo número de pessoas e bens afetados caso algo aconteça na linha de costa.

Mesmo assim, não existe nenhuma lei ou regra que obrigue as administrações dos Portos, ou gestores de embocaduras de rios, a manterem a deriva litoral nas suas áreas de influência. Estas entidades têm conhecimento dos problemas que provocam, algo já sabido há décadas de anos, e continuamente publicado em artigos da especialidade. Há até uma publicação da década de 60 que estuda as possibilidades de construção de um sistema bypass de areias para a embocadura da Ria de Aveiro.

A primeira parte desta tese é uma exaustiva revisão bibliográfica para determinar o que tem sido feito em todo o mundo utilizando a tecnologia “Sand Bypass”. Na segunda parte há um foco em determinar possíveis maneiras de implementação de um sistema destes nos dois casos de estudo portugueses.

PALAVRAS-CHAVE: Sistemas Permanentes de Alimentação Artificial de Praias, Sistemas Bypass de Areias, Erosão Costeira, Porto de Aveiro, Porto da Figueira da Foz
# Table of Contents

**Acknowledgements** .................................................................................................................. i

**Abstract** ................................................................................................................................... iii

**Resumo** ...................................................................................................................................... v

1. GENERAL FRAMEWORK ........................................................................................................... 1
   1.1. Coastal Erosion and Its Main Causes in Portugal ................................................................. 1
   1.2. Aveiro .................................................................................................................................. 1
   1.3. Figueira da Foz .................................................................................................................... 3
   1.4. Bypass as a Solution for Coastal Erosion ........................................................................... 4
      1.4.1. What is a Bypass System and How it Works ................................................................. 4
      1.4.1.1. Fixed systems ........................................................................................................... 5
      1.4.1.2. Mobile systems ....................................................................................................... 6
      1.4.1.3. Semimobile systems ............................................................................................... 7
      1.4.2. First Bypass Systems to be Operated ....................................................................... 7
      1.4.2.1. Viareggio Harbour, Italy ......................................................................................... 8
      1.4.2.2. Lake Worth Inlet, United States of America ........................................................... 8

2. LONGSHORE SEDIMENT TRANSPORT ..................................................................................... 9
   2.1. Longshore Sediment Transport ............................................................................................ 9
      2.1.1. External Factors that Influence the Sediment Transport .............................................. 10
      2.1.1.1. Water Flow ............................................................................................................ 10
      2.1.1.2. Water Level and Weather Events .......................................................................... 11
      2.1.1.3. Human Influence .................................................................................................. 11
      2.1.2. Douro River and Its Importance .................................................................................. 12
      2.1.3. Sand Trapping and Its Consequences Along Portuguese Coastline ............................ 13
      2.1.3.1. Leixões Port Influence ......................................................................................... 13
      2.1.3.2. Douro River and Aveiro Port Influence .................................................................. 14
      2.1.3.3. Figueira da Foz Port Influence .............................................................................. 17
      2.1.3.4. Nazaré Promontory Influence ............................................................................. 18
3. DREDGING AND EVOLUTION OF THE BEACH PROFILE

3.1. DREDGING SPECIFICATIONS IN AVEIRO AND FIGUEIRA DA FOZ PORTS

3.1.1. AVEIRO PORT

3.1.2. FIGUEIRA DA FOZ PORT

3.2. DREDGING RECORDS IN AVEIRO PORT

3.2.1. OVERALL ANALYSIS

3.2.2. SUMMARY TABLE AND STATISTICAL ANALYSIS

3.2.2.1. Volume per Sand Placement Area

3.2.2.2. Dredged Volume per Year and Respective Cost

3.2.2.3. Type of Dredging and Cost per Cubic Meter

3.2.2.4. Dredged Volume per Month

3.3. DREDGING RECORDS IN FIGUEIRA DA FOZ PORT

3.3.1. OVERALL ANALYSIS

3.3.2. SUMMARY TABLE AND STATISTICAL ANALYSIS

3.3.2.1. Volume per Sand Placement Area

3.3.2.2. Dredged Volume per Year and Respective Cost

3.3.2.3. Type of Dredging and Cost per Cubic Meter

3.3.2.4. Dredged Volume Per Month

3.4. AVEIRO AND FIGUEIRA DA FOZ PORT INFLUENCE IN THE ADJACENT AREAS

3.4.1. AVEIRO PORT INFLUENCE

3.4.2. FIGUEIRA DA FOZ PORT INFLUENCE

3.5. PROFILES LOCATION

3.5.1. AVEIRO PORT ADJACENT AREAS

3.5.2. FIGUEIRA DA FOZ PORT ADJACENT AREAS

3.6. ACCUMULATED VOLUME OF SAND IN THE UPDRIFT SIDE OF THE PORT

3.6.1. LONGSHORE SEDIMENT TRANSPORT IN PORTUGAL

3.6.2. CALCULATION METHODS

3.6.3. AVEIRO PORT

3.6.4. FIGUEIRA DA FOZ PORT

3.6.5. BEACH PROFILE EVOLUTION OF AVEIRO PORT UPDRIFT BEACH

3.6.6. BEACH PROFILE EVOLUTION OF FIGUEIRA DA FOZ PORT UPDRIFT BEACH
4. **BIBLIOGRAPHIC REVIEW AND INTERNATIONAL ANALOGOUS CASES OF SAND BYPASS** .......................................................... 55

4.1. **LITERATURE REVIEW** ........................................................................................................ 55

4.1.1. METHODOLOGY ........................................................................................................ 55

4.1.2. BIBLIOGRAPHIC DATABASE .................................................................................. 56

4.1.3. STATISTICAL ANALYSIS ......................................................................................... 62

4.1.3.1. Bypass systems around the world ................................................................. 62

4.1.3.2. Starting year of the sand bypass operations ............................................. 63

4.1.3.3. Type of sand bypass system ...................................................................... 64

4.1.3.4. Wave regime .................................................................................................. 65

4.1.3.5. Tide range ...................................................................................................... 66

4.1.3.6. Annual bypassed volume ............................................................................. 66

4.2. **INTERNATIONAL ANALOGOUS CASES OF SAND BYPASS** ............................................ 67

4.2.1. CHOOSING CRITERIA ....................................................................................... 67

4.2.2. CHARACTERISTICS OF THE SAND BYPASS SYSTEMS ........................................... 67

4.2.3. WAVE REGIME ANALYSIS ............................................................................. 68

4.2.3.1. World wave energy resource map ........................................................... 68

4.2.3.2. Wave buoys reports .................................................................................. 69

4.2.3.3. Storm analysis ............................................................................................ 71

4.3. **OVERALL ANALYSIS** .......................................................................................... 72

4.3.1. INDIAN RIVER INLET, UNITED STATES OF AMERICA ........................................... 72

4.3.1.1. Background .................................................................................................. 72

4.3.1.2. Plant data ..................................................................................................... 73

4.3.1.3. Process Description .................................................................................. 74

4.3.1.4. Operational Problems ............................................................................ 74

4.3.1.5. Costs ........................................................................................................ 74

4.3.2. NERANG RIVER, AUSTRALIA ................................................................................. 75

4.3.2.1. Background .................................................................................................. 75

4.3.2.2. Plant data ..................................................................................................... 76

4.3.2.3. Process Description .................................................................................. 77

4.3.2.4. Operational Problems ............................................................................ 79

4.3.2.5. Costs ........................................................................................................ 79

4.3.3. PORT OF DURBAN, SOUTH AFRICA .................................................................... 81
5. SAND BYPASS AS A MITIGATION FOR BEACH EROSION DOWNDrift OF AVEIRO AND FIGUEIRA DA FOZ Ports .... 97

5.1. SAND BYPASS SYSTEM AND ITS ADVANTAGES/DISADVANTAGES ................................................. 97

5.1.1. APPLICATION OF SAND BYPASS SYSTEMS .................................................................................. 97

5.1.2. FIXED SAND BYPASS SYSTEM IN PORTUGAL VS CURRENT SOLUTIONS .................................... 97

5.1.2.1. Aveiro Lagoon Mouth ............................................................................................. 100

5.1.2.2. Figueira da Foz River Mouth .................................................................................. 101

5.2. EXISTING TYPES OF SAND BYPASSING SYSTEMS ................................................................. 101

5.2.1. MOBILE SAND BYPASS SYSTEM ......................................................................................... 102

5.2.1.1. Fort Pierce Inlet, Florida, USA .................................................................................. 102

5.2.1.2. Point Roberts Marina, Washington, USA .................................................................. 103

5.2.1.3. Costa da Caparica, Portugal .................................................................................... 104

5.2.1.4. Visakhapatnam, India .................................................................................................. 105

5.2.2. SEMI MOBILE SAND BYPASS SYSTEM .............................................................................. 106

5.2.2.1. Channel Islands Harbour, California, USA ................................................................ 106

5.2.2.2. Port of Durban, Durban, South Africa .......................................................................... 107

5.2.2.3. Hillsboro Inlet, Florida, USA ...................................................................................... 107
6. POSSIBLE SOLUTIONS OF SAND BYPASS SYSTEMS FOR AVEIRO AND FIGUEIRA DA FOZ PORTS

6.1. AVEIRO PORT POSSIBLE SOLUTIONS

6.1.1. CRANE MOUNTED JET PUMP IN THE UPDRIFT BEACH

6.1.1.1. Operation Cost Analysis

6.1.1.2. Construction Cost Analysis

6.1.2. WEIR JETTY AND SAND PLACEMENT THROUGH FLOATING PIPELINE TECHNIQUE

6.1.2.1. Construction Cost Analysis

6.1.2.2. Operation Cost Analysis

6.1.3. WEIR JETTY AND SAND PLACEMENT THROUGH RAINBOW TECHNIQUE

6.1.3.1. Operation Cost Analysis

6.1.3.2. Construction Cost Analysis

6.1.4. WEIR JETTY AND SAND PLACEMENT IN HOPPER SYSTEM TO LATER DISCHARGE THROUGH PIPELINE SYSTEM

6.1.4.1. Construction Cost Analysis

6.1.4.2. Operation Cost Analysis

6.1.5. WEIR JETTY AND SAND PLACEMENT DOWNDRIFT THROUGH PIPELINE SYSTEM

6.1.5.1. Construction Cost Analysis

6.1.5.2. Operation Cost Analysis

6.1.6. JETTY HOUSING JET PUMPS, PUMP STATION CONNECTED TO A CLEAR WATER INTAKE AND PIPELINE SYSTEM WITH MULTIPLE DISCHARGE LOCATIONS

6.1.6.1. Construction Cost Analysis

6.1.6.2. Operation Cost Analysis

6.2. FIGUEIRA DA FOZ PORT POSSIBLE SOLUTIONS

6.2.1. CRANE MOUNTED JET PUMP IN THE UPDRIFT BEACH

6.2.1.1. Operation Cost Analysis

6.2.1.2. Construction Cost Analysis

6.2.2. WEIR JETTY AND SAND PLACEMENT THROUGH FLOATING PIPELINE TECHNIQUE

6.2.2.1. Construction Cost Analysis
6.2.2.2. Operation Cost Analysis ................................................................. 137
6.2.3. WEIR JETTY AND SAND PLACEMENT THROUGH RAINBOW TECHNIQUE ................................................................. 138
6.2.3.1. Construction Cost Analysis ............................................................... 138
6.2.3.2. Operation Cost Analysis .................................................................. 138
6.2.4. WEIR JETTY AND SAND PLACEMENT IN HOPPER SYSTEM TO LATER DISCHARGE THROUGH PIPELINE SYSTEM ................................................................. 139
6.2.4.1. Construction Cost Analysis ............................................................... 139
6.2.4.2. Operation Cost Analysis .................................................................. 139
6.2.5. WEIR JETTY AND SAND PLACEMENT DOWNDRIFT THROUGH PIPELINE SYSTEM ................................................................. 140
6.2.5.1. Construction Cost Analysis ............................................................... 141
6.2.5.2. Operation Cost Analysis .................................................................. 141
6.2.6. JETTY HOUSING JET PUMPS, PUMP STATION CONNECTED TO A CLEAR WATER INTAKE AND PIPELINE SYSTEM WITH MULTIPLE DISCHARGE LOCATIONS ................................................................. 142
6.2.6.1. Construction Cost Analysis ............................................................... 143
6.2.6.2. Operation Cost Analysis .................................................................. 144
6.3. FEASIBILITY STUDY OF THE VARIOUS POSSIBLE SOLUTIONS FOR EACH PORT ................................................................. 146
6.3.1. CRANE MOUNTED JET PUMP IN THE UPDRIFT BEACH ................................................................. 149
6.3.2. JETTY HOUSING JET PUMPS, PUMP STATION CONNECTED TO A CLEAR WATER INTAKE AND PIPELINE SYSTEM WITH MULTIPLE DISCHARGE LOCATIONS ................................................................. 149
6.3.3. WEIR JETTY AND SAND PLACEMENT THROUGH RAINBOW TECHNIQUE ................................................................. 149
6.3.4. WEIR JETTY AND SAND PLACEMENT IN HOPPER SYSTEM TO LATER DISCHARGE THROUGH PIPELINE SYSTEM ................................................................. 150
6.3.5. WEIR JETTY AND SAND PLACEMENT DOWNDRIFT THROUGH FLOATING/BURIED PIPELINE SYSTEM ................................................................. 150
6.3.6. WEIR JETTY AND SAND PLACEMENT DOWNDRIFT THROUGH FLOATING PIPELINE SYSTEM ................................................................. 150

7. CONCLUSIONS AND FUTURE DEVELOPMENTS ........................................ 151
7.1. CONCLUSIONS ...................................................................................... 151
7.2. FUTURE DEVELOPMENTS ..................................................................... 152
REFERENCES ............................................................................................. 155

APPENDIXES ............................................................................................ 157
LIST OF FIGURES

Fig. 1 – Overview of Aveiro Port (2017, Google Earth) .................................................................2
Fig. 1.1 – Overview of Aveiro Port (2017, Google Earth) .................................................................2
Fig. 1.2 - Overview of Figueira da Foz Port (May 2017, Google Earth) .........................................3
Fig. 1.3 – Fixed Bypass System, Nerang River, Australia (Sediments Management at Inlets and Harbors, 2003) ........................................................................................................5
Fig. 1.4 – Schematic view of a Mobile Sand Bypass System (Sediments Management at Inlets and Harbors, 2003) ........................................................................................................6
Fig.1.5 – Schematic view of a Semimobile Sand Bypass System (Sediments Management at Inlets and Harbors, 2003) .........................................................................................................7
Fig. 1.6 – Historical Overview Scheme of Viareggio Harbour (Sediments Management at Inlets and Harbors, 2003) ........................................................................................................7
Fig. 1.7 – Original Bypass System in South Lake Worth Inlet (Joseph M. Caldwell, 2010) ..........8
Fig. 2.1 – Influence of water flow in sediment transport (fondriest.com) ........................................10
Fig. 2.2 – Dam and its influence in sediment transport (aemstatic-ww1.azureedge.net) ...............12
Fig. 2.3 – Flooding in Douro River (farm1.static.flickr.com) ...........................................................12
Fig. 2.4 – Main Sand Traps along the Portuguese Coastline .............................................................13
Fig. 2.5 – Beach near “Castelo do Queijo”, Porto (guiadacidade.pt) ..............................................14
Fig. 2.6 – Furadouro, an endangered city by the sea (portugalfotografiaaerea.blogspot.com) ....15
Fig. 2.7 – Cortegaça, another victim of inadequate coastline planning (portugalfotografiaaerea.blogspot.com) .......................................................................................................................15
Fig. 2.8 – Vagueira Beach, its adherent structures and inappropriate constructions close to the sea (portugalfotografiaaerea.blogspot.com) .............................................................................16
Fig. 2.9 – Tocha beach and its inexistent effects of beach erosion (portugalfotografiaaerea.blogspot.com) ..............................................................................................................................16
Fig. 2.10 – Figueira da Foz River Mouth (where port is located) and consequences updrift and downdrift (Isa Alexandrina Lopes, 2017) .......................................................................................................17
Fig. 2.11 – Effects of beach erosion downdrift of Figueira da Foz (portugalfotografiaaerea.blogspot.com) .................................................................................................................................17
Fig. 2.12 – Nazaré Promontory and updrift beach (CCDRC, 2008) ................................................18
Fig. 2.13 – Nazaré downdrift beach in 1950s and 6 decades later (cabo-carvoeiro-historico.blogspot.pt and portugaltours.com.pt) .......................................................................................................18
Fig. 3.1 – Dredging Sources in Aveiro Port (2010-2016) .............................................................22
Fig. 3.2 – Sand Placement Areas in Aveiro Port (2010-2016) .......................................................23
Fig. 3.3 – Volume per Sand Placement Area, Aveiro Port .............................................................25
Fig. 3.4 – Before, During and After the biggest storm of the year, Vagueira Beach .........................26
Fig. 4.4 – Number of Sand Bypass Systems per Starting Year of Operations ........................................64
Fig. 4.5 – Number of sand bypass systems by type of system .............................................................65
Fig. 4.6 – Number of sand bypass systems for each range of wave energy .......................................65
Fig. 4.7 – Number of sand bypass systems for each tide range ..........................................................66
Fig. 4.8 – Numer of Sand Bypass Systems for each Range of Bypassed Volume ...............................67
Fig. 4.9 – World wave energy resource map (analogous cases locations) ...........................................68
Fig. 4.10 – Hs comparison between the 5 international analogous cases .........................................70
Fig. 4.11 – Indian River, United States of America ............................................................................72
Fig. 4.12 – Scheme of the sand bypass system in Indian River Inlet ................................................73
Fig. 4.13 – Overview of the sand bypass system in Nerang River ......................................................76
Fig. 4.14 – Scheme of the jetty (www.griffith.edu.au) .........................................................................78
Fig. 4.15 – Debris from the cleaning of a single jet pump (erdc-library.erdc.dren.mil) .......................79
Fig. 4.16 – Hopper, the main element of Port of Durban sand bypass system nowadays .................81
Fig. 4.17 – Pipelines’ Material before and after sand bypass system renewal (rho-tech.co) .............84
Fig. 4.18 – Schematic view of Port of Ngqura Sand Bypass System ..................................................85
Fig. 4.19 – Jetty scheme (Transnet, 2017) .........................................................................................86
Fig. 4.20 - Jetty overview (Transnet, 2017) ......................................................................................87
Fig. 4.21 – Sandtrap transversal profile (Transnet, 2017) .................................................................88
Fig. 4.22 – Overview of Tweed River Sand Bypass System (tweedsandbypass.nsw.gov.au) ..........91
Fig 4.23 – Jet pump scheme (coastadapt.com.au) .............................................................................92
Fig 4.24 – Overview of the Tweed River sand Bypass System (tweedsandbypass.nsw.gov.au) .......94
Fig. 5.1 – Schematic view of Fort Pierce Sand Bypass System .........................................................102
Fig. 5.2 – Schematic view of Point Roberts Sand Bypass System .....................................................103
Fig. 5.3 – Schematic View of Beach nourishment through Floating Pipeline in Costa da Caparica (Rohde Nielsen, 2007) .................................................................104
Fig 5.4 – Schematic view of Visakhapatnam Sand Bypass System..................................................105
Fig. 5.5 – Schematic view of Channel Islands Harbour Sand Bypass System ................................106
Fig. 5.6 – Schematic view of Port of Durban sand bypass system ....................................................107
Fig. 5.7 – Schematic view of Hilsboro Sand Bypass System .............................................................108
Fig. 5.8 – Schematic view of Indian River Sand Bypass System ......................................................109
Fig. 5.9 – Schematic view of Lake Worth Inlet Sand Bypass System ..............................................110
Fig. 5.10 – Schematic view of Tweed River Sand Bypass System ....................................................111
Fig. 6.1 – Schematic view of a Detached Breakwater solution, Aveiro Port ......................................114
Fig. 6.2 – Schematic view of a Crane Mounted Jet Pump in a pump station in the updrift breakwater, Aveiro Port .......................................................... 114

Fig. 6.3 – Schematic view of Bulldozers collecting sand and transportation by truck, Aveiro Port .... 115

Fig. 6.4 – Schematic View of Sand Trapping breakwater, Aveiro Port ........................................ 115

Fig. 6.5 – Crane Mounted Jet Pump in Indian River (Dan Brower, 2012) ........................................ 116

Fig. 6.6 – Schematic view of Aveiro Port with a Quadruple Crane Munted Jet Pump System ........ 118

Fig. 6.7 – Floating Pipeline Technique in Visakapatnam, India (thehindu.com) .............................. 119

Fig. 6.8 – Cross section of the northern breakwater of Aveiro Port and area to remove in order to create the Weir jetty ........................................................................................................................................ 120

Fig. 6.9 – Rainbow Technique in Visakapatnam, India (thehindu.com) ........................................ 121

Fig. 6.10 – Schematic view of Aveiro Port with a Weir Jetty and Sand Bypass via Rainbow technique ........................................................................................................................................ 122

Fig. 6.11 – Schematic view of Aveiro Port with a Weir Jetty and Sand Bypass via Hopper System Technique ........................................................................................................... 123

Fig. 6.12 – Schematic view of Sand Hopper System Operation (iol.co.za, 2017) ............................... 124

Fig. 6.13 – Suction Dredger equipped with pumping system and floating pipeline (José Ruas Company, 2017) ........................................................................................................................................ 125

Fig. 6.14 – Schematic view of Aveiro Port with a Weir Jetty and Floating/burried Pipeline Sand Bypass System ........................................................................................................... 126

Fig. 6.15 – Jetty Structure in Tweed River Sand Bypass System (coastalwatch.com) ..................... 127

Fig. 6.16 – Schematic view of the northern side elevation of a Jetty Structure in Aveiro Port Updrift beach ........................................................................................................................................ 128

Fig. 6.17 – Initial modulus of subgrade reaction depending on relative density and angle of internal friction of sand (COPYRIGHT 2003; American Petroleum Institute) ........................................................................................................................................ 129

Fig. 6.18 – Pile cross-section and respective materials ........................................................................................................................................ 130

Fig. 6.19 – Beam Cross-section and its material ........................................................................................................................................ 130

Fig 6.20 – Forces and Loads acting on the porch ........................................................................................................................................ 132

Fig. 6.21 – Schematic view of a Fixed Sand Bypass System in Aveiro Port ........................................ 134

Fig. 6.22 – Schematic view of Aveiro Port with a Quadruple Crane Mounted Jet Pump System ......... 137

Fig. 6.23 – Schematic view of Figueira da Foz Port with a Weir Jetty and Sand Bypass via floating pipeline technique ........................................................................................................................................ 138

Fig. 6.24 – Schematic view of Figueira da Foz Port with a Weir Jetty and Sand Bypass via Rainbow technique ........................................................................................................................................ 139

Fig. 6.25 – Schematic view of Figueira da Foz Port with a Weir Jetty and Sand Bypass via Hopper System Technique ........................................................................................................................................ 140

Fig. 6.26 – Schematic view of Aveiro Port with a Weir Jetty and Floating Pipeline Sand Bypass System ........................................................................................................................................ 142
<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fig. 6.27 – Northern Side Elevation of the jetty structure in Figueira da Foz Port Updrift beach</td>
<td>143</td>
</tr>
<tr>
<td>Fig. 6.28 – Schematic view of a Fixed Sand Bypass System in Figueira da Foz Port</td>
<td>145</td>
</tr>
<tr>
<td>Fig. 1 – Aveiro/Figueira da Foz Wave Records, 2011</td>
<td>160</td>
</tr>
<tr>
<td>Fig. 2 – Ngqura Wave Records, 2011</td>
<td>160</td>
</tr>
<tr>
<td>Fig. 3 – Durban Wave Records, 2011</td>
<td>161</td>
</tr>
<tr>
<td>Fig. 4 – Indian River Wave Records, 2011</td>
<td>161</td>
</tr>
<tr>
<td>Fig. 5 – Tweed/Nerang River Wave Records, 2011</td>
<td>162</td>
</tr>
<tr>
<td>Fig. 6 – Aveiro/Figueira da Foz Wave Records, 2012</td>
<td>162</td>
</tr>
<tr>
<td>Fig. 7 – Ngqura Wave Records, 2012</td>
<td>163</td>
</tr>
<tr>
<td>Fig. 8 – Durban Wave Records, 2012</td>
<td>163</td>
</tr>
<tr>
<td>Fig. 9 – Indian River Wave Records, 2012</td>
<td>164</td>
</tr>
<tr>
<td>Fig. 10 – Tweed/Nerang River Wave Records, 2012</td>
<td>164</td>
</tr>
<tr>
<td>Fig. 11 – Aveiro/Figueira da Foz Wave Records, 2013</td>
<td>165</td>
</tr>
<tr>
<td>Fig. 12 – Ngqura Wave Records, 2013</td>
<td>165</td>
</tr>
<tr>
<td>Fig. 13 – Durban Wave Records, 2013</td>
<td>166</td>
</tr>
<tr>
<td>Fig. 14 – Indian River Wave Records, 2013</td>
<td>166</td>
</tr>
<tr>
<td>Fig. 15 – Tweed/Nerang River Wave Records, 2013</td>
<td>167</td>
</tr>
<tr>
<td>Fig. 16 – Aveiro/Figueira da Foz Wave Records, 2014</td>
<td>167</td>
</tr>
<tr>
<td>Fig. 17 – Ngqura Wave Records, 2014</td>
<td>168</td>
</tr>
<tr>
<td>Fig. 18 – Durban Wave Records, 2014</td>
<td>168</td>
</tr>
<tr>
<td>Fig. 19 – Indian River Wave Records, 2014</td>
<td>169</td>
</tr>
<tr>
<td>Fig. 20 – Tweed/Nerang River Wave Records, 2014</td>
<td>169</td>
</tr>
<tr>
<td>Fig. 21 – Aveiro/Figueira da Foz Wave Records, 2015</td>
<td>170</td>
</tr>
<tr>
<td>Fig. 22 – Ngqura Wave Records, 2015</td>
<td>170</td>
</tr>
<tr>
<td>Fig. 23 – Durban Wave Records, 2015</td>
<td>171</td>
</tr>
<tr>
<td>Fig. 24 – Indian River Wave Records, 2015</td>
<td>171</td>
</tr>
<tr>
<td>Fig. 25 – Tweed/Nerang River Wave Records, 2015</td>
<td>172</td>
</tr>
<tr>
<td>Fig. 26 – Aveiro/Figueira da Foz Wave Records, 2016</td>
<td>172</td>
</tr>
<tr>
<td>Fig. 27 – Ngqura Wave Records, 2016</td>
<td>173</td>
</tr>
<tr>
<td>Fig. 28 – Durban Wave Records, 2016</td>
<td>173</td>
</tr>
<tr>
<td>Fig. 29 – Indian River Wave Records, 2016</td>
<td>174</td>
</tr>
<tr>
<td>Fig. 30 – Tweed/Nerang River Wave Records, 2016</td>
<td>174</td>
</tr>
<tr>
<td>Fig. 31 – Location of Beach Profiles, Aveiro Coastline</td>
<td>176</td>
</tr>
<tr>
<td>Figure</td>
<td>Location</td>
</tr>
<tr>
<td>--------</td>
<td>---------------------------------------</td>
</tr>
<tr>
<td>Fig. 32</td>
<td>P1</td>
</tr>
<tr>
<td>Fig. 33</td>
<td>P2</td>
</tr>
<tr>
<td>Fig. 34</td>
<td>P3</td>
</tr>
<tr>
<td>Fig. 35</td>
<td>P4</td>
</tr>
<tr>
<td>Fig. 36</td>
<td>P5</td>
</tr>
<tr>
<td>Fig. 37</td>
<td>P6</td>
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<tr>
<td>Fig. 38</td>
<td>P7</td>
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<tr>
<td>Fig. 39</td>
<td>P8</td>
</tr>
<tr>
<td>Fig. 40</td>
<td>P9</td>
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<tr>
<td>Fig. 41</td>
<td>P10</td>
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<td>Fig. 42</td>
<td>P11</td>
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<td>Fig. 43</td>
<td>P12</td>
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<td>Fig. 44</td>
<td>P1</td>
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<td>Fig. 45</td>
<td>P2</td>
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<td>Fig. 46</td>
<td>P3</td>
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<td>Fig. 47</td>
<td>P4</td>
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<tr>
<td>Fig. 48</td>
<td>P5</td>
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<tr>
<td>Fig. 49</td>
<td>P6</td>
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<td>Fig. 50</td>
<td>P7</td>
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<td>Fig. 51</td>
<td>P8</td>
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<tr>
<td>Fig. 52</td>
<td>P9</td>
</tr>
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<td>Fig. 53</td>
<td>P10</td>
</tr>
<tr>
<td>Fig. 54</td>
<td>P11</td>
</tr>
<tr>
<td>Fig. 55</td>
<td>P12</td>
</tr>
<tr>
<td>Fig. 56</td>
<td>Location of Beach Profiles, Figueira da Foz Coastline</td>
</tr>
<tr>
<td>Fig. 57</td>
<td>P1</td>
</tr>
<tr>
<td>Fig. 58</td>
<td>P2</td>
</tr>
<tr>
<td>Fig. 59</td>
<td>P3</td>
</tr>
<tr>
<td>Fig. 60</td>
<td>P4</td>
</tr>
<tr>
<td>Fig. 61</td>
<td>P5</td>
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<td>Fig. 62</td>
<td>P6</td>
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<tr>
<td>Fig. 63</td>
<td>P7</td>
</tr>
<tr>
<td>Fig. 64</td>
<td>P8</td>
</tr>
</tbody>
</table>
Fig. 65 – P9 .................................................................197
Fig. 66 – P10 .................................................................197
Fig. 67 – P11 .................................................................198
Fig. 68 – P12 .................................................................198
Fig. 69 – P13 .................................................................199
Fig. 70 – P14 .................................................................199
Fig. 71 – P15 .................................................................200
Fig. 72 – Hmax Records, 2010-2016 in Sand Bypass Analogous Cases ..................................202
### LIST OF TABLES

Table 3.1 – Dredging depths in Aveiro Port .................................................................................. 20
Table 3.2 – Dredging depths in Figueira da Foz Port .................................................................. 20
Table 3.3 – Dredging records in Aveiro Port ............................................................................... 24
Table 3.4 – Legend of Sand Placement Areas .............................................................................. 25
Table 3.5 – Dredging records in Figueira da Foz Port Adjacent Areas .......................................... 35
Table 3.6 – Legend of dredging locations ....................................................................................... 35
Table 3.7 – Legend of sand placement areas .................................................................................. 36
Table 3.8 – Dredged volume per year in Tweed River Entrance (tweedsandbypass.nsw.gov.au) .... 37
Table 3.9 – Calculation method in Aveiro .................................................................................... 46
Table 3.10 – Calculation method in Figueira da Foz .................................................................... 47
Table 3.11 – Sand balance updrift of Aveiro Port .......................................................................... 47
Table 3.12 – Silting, Desilting and their possible reasons ................................................................. 48
Table 3.13 – Sand balance updrift of Figueira da Foz Port ............................................................... 48
Table 3.14 – Retreat/advancement of the coastline in Profile 1, Aveiro .......................................... 49
Table 3.15 – Retreat/advancement of the coastline in Profile 2, Aveiro .......................................... 51
Table 3.16 – Annual advancement/retreat of Aveiro Port adjacent areas ...................................... 51
Table 3.17 – Retreat/advancement of the coastline in Profile 2, Figueira da Foz ......................... 52
Table 3.18 – Retreat/advancement of the coastline in Profile 3, Figueira da Foz ......................... 54
Table 3.19 – Annual advancement/retreat of Figueira da Foz Port adjacent areas ......................... 54
Table 4.1 – Bibliographic database .............................................................................................. 57
Table 4.2 – Characteristics of Case Studies ................................................................................... 68
Table 4.3 – Number of storms per year in each location of the sand bypass systems .................... 71
Table 4.4 – Bypassed volume per year ......................................................................................... 74
Table 4.5 – Bypassed Volume, hours of operation and costs per year ............................................. 79
Table 4.6 – Bypassed volume per year, Port of Durban ................................................................. 82
Table 4.7 – Bypassed volumes per year (Schmidt, 2016) ................................................................. 90
Table 4.8 – Bypassed volume and costs per year .......................................................................... 96
Table 5.1 – Advantages and Disadvantages of fixed sand bypass systems ....................................... 98
Table 5.2 – Comparison between dredging in Portugal and bypassing ......................................... 99
Table 6.1 – Total cost of construction of a Quadruple Crane Mounted Sand Bypass System in Aveiro Port ......................................................................................................................... 118
Table 6.2 – Wave force calculation ............................................................................................... 130
Table 6.3 – Dead Load calculation .................................................................................................................. 131
Table 6.4 – Wind Load Calculation .................................................................................................................. 131
Table 6.5 – Comparison between Aveiro and Port of Ngqura Bypass features ........................................... 132
Table 6.6 – Cost comparison between sand bypass operation in Aveiro and Ngqura Ports .................. 133
Table 6.7 – Comparison between Australian Cases and Aveiro Port operational sand bypass cost .. 134
Table 6.8 – Total cost of construction of a Quadruple Crane Mounted Sand Bypass System .............. 136
Table 6.9 – Comparison between Figueira da Foz and Port of Ngqura Bypass features ...................... 143
Table 6.10 – Cost comparison between sand bypass operation in Figueira da Foz and Ngqura Ports ........................................................................................................................................ 144
Table 6.11 – Comparison between Australian Cases and Aveiro Port operational sand bypass cost 144
Table 6.12 – Advantages, Disadvantages and Costs for construction and operation of 6 types of Sand Bypass Systems, Aveiro Port ........................................................................................................................................ 1457
Table 6.13 - Advantages, Disadvantages and Costs for construction and operation of 6 types of Sand Bypass Systems, Figueira da Foz Port .................................................................................................................. 1458
SYMBOLS AND ABBREVIATIONS

$C_D$ – Drag Coefficient  
$F_{DM}$ – Drag Force  
$F_{IM}$ – Inertia Force  
$H$ – Height [m]  
$H_{max}$ – Maximum Wave Height [m]  
$H_s$ – Significant Wave Height [m]  
$L$ – Length [m]

Bal – Balance  
BHD – Backhoe Dredger  
CD – Chart Datum  
CSD – Cutter Suction Dredger  
EC0 – Eurocode 0  
EC1 – Eurocode 1  
EC2 – Eurocode 2  
GD – Grab Dredger  
HDPE – High Density Polyethylene  
HT – High Tide  
LNEC – Laboratório Nacional de Engenharia Civil  
MDPE – Medium Density Polyethylene  
NSW – New South Wales  
PLC – Programmable Logic Controller  
Prof – Profile  
QLD – Queensland  
Ro-Ro – Roll-on Roll-off  
Silt – Siltation  
TNPA – Transnet National Ports Authority  
TRESBP – Tweed River Entrance Sand Bypassing Project  
TSHD – Trailer Suction Hopper Dredger  
USACE – United States of Army Corps of Engineers  
Vol – Volume
1.1. COASTAL EROSION AND ITS MAIN CAUSES IN PORTUGAL

Although the winds, tides and waves at their most extreme point are a strong cause to the beach erosion, dams and breakwaters/groins are the biggest causers of this problem.

Groins have their main function as create accretion updrift but, inevitably, erosion downdrift. Along the Portuguese coast, especially downdrift of Aveiro and Figueira da Foz Ports, there are a field of groins that, after the erosion process caused by the rubble-mound breakwaters of the harbour, instead of solving the erosion problem, just postpone it downdrift causing instabilities and possible destruction of housing and recreational areas. The problem is that these housing areas, being built in unstable areas, are themselves causers of local erosion (because they destroy the natural defence against wave action). But these are just local causes of beach erosion.

The main causes of this phenomenon are the dams. When they are being built, large volumes of sediments are removed from their origin and, supposedly, go with the flow downstream of the river. The problem is that during the exploration of the dam, downstream of it, the flow is not enough to transport those large amounts of sediments. And, Douro River case speaking, there are a waterfall of dams what means that the sediments that keep their movement and go with the flow will be stopped in the next dam and so on. The most influential ones were, firstly, the sandpits which were maintained during decades and, nowadays, the runoff river sections which are caused by the dams.

1.2. AVEIRO

Aveiro is nowadays a city by the sea but its Port, in Figure 1.1, and more specifically, its inlet is only 209 years old.

Multiple storms, winds and tides influenced the creation of Aveiro Lagoon (Ria de Aveiro) in the state it is today. The inlet, opened naturally, changed its location multiple times from north to south of its current location. Municipality Reports (CMI, 2012) say that the inlet was really dangerous with lots of submerged sand banks that made the safe navigation almost impossible. Due to this instability, the housing areas around the estuary was very unstable. During winter the flow is bigger causing floods and during summer the flow is almost zero making agriculture, livestock and salt exploration an impossible activity to maintain.
According to Municipality Reports (CMI, 2012), since 1757 successive interventions from political, economic and technical point of view were done to study the perfect location for Aveiro Lagoon mouth.

Back to 3rd of April 1808, from the “hands” of two Portuguese engineers: Reinaldo Oudinot e Luis Gomes de Carvalho, that were in charge to the conception of the first big study for the open of the Aveiro’s inlet, the inlet was opened and established. Since that day the city’s story changed completely. The inlet was pretty far from the city centre, around 15 km (what could be a barrier to the prosperity and success of the harbour) but after that the city got a new identity, unique at a national and international level, international trade developed and the harbour turned into one of the most important fishery harbours in the country attracting lots of industries and, consequently, wealth to the region (that since that day was whipped by poverty, diseases and an extremely lack of hope).

After the inlet was established, with rubble-mound breakwaters, and since mid XX century, lots of jetties were enlarged and dams were built. This was a huge contribution for the harbour’s development. Engineer Von Haff projected the fishery and commercial harbours near the city and Engineer Coutinho Lima created the new plant for the restoration and exploration of these infrastructures.

Finally, in 1974, “Master Plan for Development and Valorisation for Region and Aveiro’s Port” moved the main terminal to near the inlet where it is established today, which were proof to be the best possible location.

Since 1974 a lot of improvements were made to the inlet and its surrounding area:

- Both south and north breakwater were enlarged;
- New jetties were built south of the inlet;
- More terminals, with multiple functionalities, were built;
- Navigable channel was deepened;
- Artificial sand nourishments (by dredgers).

Fig. 1.1 - Overview of Aveiro Port (2017, Google Earth)
All these measures were huge contributors to the development of Aveiro Port. However, nothing was done to re-establish the normal longshore sediment transport that was stopped with the extension of the updrift rubble-mound breakwater in 2013.

1.3. FIGUEIRA DA FOZ

Like Aveiro, Figueira da Foz inlet, in Figure 1.2, was always considered a dangerous inlet, although safety conditions only got worse sometimes in history, probably after the end of 18th century. The economic and strategic interest of this harbour was always recognized but the constant silting of the inlet was a hard problem to deal with.

Before the works that were carried out in the mid-19th century the north part of Figueira da Foz was covered by limestone in form of sandspits and natural reefs that were constantly changing the course of currents and made the access to the harbour an almost impossible task.

The south part, that was low and sandy, was very affected by the constant changes in swell, wind direction and river flow. This made the inlet very inconstant and subject to the action of the natural elements.

Therefore multiple shipwrecks are documented, lots of fishermen deaths caused by, only between 1876 and 1884, 20 notable accidents. The depth of the inlet was also very low, reaching an absolute minimum of 2 m in 1837 during the low tide, making the safe navigation almost impossible.

According to Figueira da Foz Port Authority documents (APFF, 2016), until 1966, when the inlet was finally established with the construction of the north and south breakwater, lots of studies were made and dozens of committees were nominated in order to find a solution for the permanent maintenance of this important harbour.
In 30th of October 1966, by the “hands” of Portuguese Company of Maritime Works, after the first studies made by Portuguese Laboratory of Civil Engineering (LNEC), the north and south breakwaters were finally ready with a length of 900 and 950 m respectively. The total cost of this construction was 350,000 € and made possible the strong evolution of Figueira da Foz economic life.

In 1985 the harbour reached the mark of 500,000 tons of exported/imported material per year and, to prove the evolution of this harbour, in the first half of 2016 the quantity of exported/imported material was almost 2 million tons.

Since 1966, the year of the establishment of Figueira da Foz harbour, a lot of big constructions were carried out by the multiple companies that were in charge of this harbour administration:

- Constant dredging to increase the depth of the navigable channel;
- New and bigger terminals;
- Jetties downdrift of the harbour;
- Extension of the existing breakwaters.

But, like in Aveiro’s situation, anything was done to fill the longshore sediment trap that was created with the implementation of the northern breakwater.

1.4. Bypass As A Solution For Coastal Erosion

1.4.1. What is a Bypass System and How it Works

A lot of solutions were thought and implemented since erosion problems started to be noticed in the downdrift beaches near inlets or harbour structures. The first thing that matter is to ensure that the accretion updrift is not too much and the erosion downdrift does not affect housing areas or cause changes to the normal operation of different ecosystems. Beyond this, navigation channels always tend to deposit large amounts of the longshore littoral drift materials in it, what represent a big concern to harbour administrations that must have a significant depth in the navigation channel in order to receive ships as big as possible. These concerns with navigation were constantly solved with periodic dredging, what means constant outgoings - that just retard the problem instead of solving it, what could be mitigated with beach nourishment.

Bypass systems have the capacity to collect the longshore sediment transport before it natural bypasses the inlets and possibly deposit there and at the same time collect that sand and send it to the downdrift eroded areas. There are plenty of ways to do it, first to suck the sand updrift, and then to deposit it downdrift, namely:

- Fixed systems (Figure 1.3);
- Mobile systems (Figure 1.4);
- Semimobile systems (Figure 1.5).
1.4.1.1. Fixed systems

Fixed systems are more used when the volume to bypass is extremely relevant (in the order of hundreds of thousands of cubic meters per year). They also have the capability to work in all weather conditions (big waves, strong winds, high and low tides, winter, summer, etc.) and the possibility to work during night and take advantage of the lower electricity rates. These systems consist of a jetty (perpendicular to the beach) with a built-in pump system, connected to an inland pump station which in turn has multiple outlet pipelines that will lead to the discharge points. The pump system includes a clean water intake through a submersible pump, usually in the navigation channel (where the water is presumably free of debris), and multiple jet pumps in the jetty. These jet pumps are hydraulically powered pumps with no moving parts and work like this:

1. The clean water from the navigation channel passes with high velocity (motive flow);
2. Is then forced through a reduction nozzle to create a high-velocity (low-pressure) jet;
3. Upon exiting the nozzle, the jet entrains the surrounding fluid and forces the mixture through a mixing chamber and diffuser;
4. Finally, it goes through the discharge line.

![Diagram of Fixed Bypass System](image)

Fig. 1.3 – Fixed Bypass System, Nerang River, Australia (Sediments Management at Inlets and Harbors, 2003)

When the nozzle/suction opening is buried in the sand, a sand-water (slurry) mixture is drawn into the discharge line. This discharge line is usually a gravitational flume that drives the slurry to the pump station. In the pump station there are centrifugal pumps to pump the slurry to the discharge points through the pipeline (possibly across channel bottom) with booster in its way if necessary.

The system incorporates a programmable logic controller (PLC) to control the jet pumps automatically. Sand transported into the sand trap (jetty area) is removed by the jet pumps that operate when there is enough sand available in the affected area of each one. Usually multiple jet pumps can operate at the same time depending on which ones have more sand.

This kind of systems have a high cost of installation but the operation costs are significantly lower that the system using dredges. It also requires a permanent team of qualified workers (mostly engineers and electricians) and two or three plant operators.
1.4.1.2. Mobile systems

Mobile systems usually include a dredge, holder of a pump station and pipeline. The dredge has a little delimited borrow area where it can get the sand but it has to be an area reasonably protected from wave action and this is the main problem with the use of mobile sand bypass systems. They are dependent of the wave and tide conditions: if the waves are too big and/or the tide is too low, the borrow area turns very limited and if the available area (where there are no waves and the tide permits the dredge to operate) is free of sand the bypass operations are impossible to run. That is the advantage of semimobile systems compared to this one.

The pipeline linked to the dredge also allows a great freedom in the choice of the discharge points which is a good advantage compared to the fixed bypass systems.
1.4.1.3. Semimobile systems

Semimobile systems work at the same way as mobile ones but with the particularity that the borrow area is a sandtrap. This sandtrap area (delimited by groins, composed by a weir jetty or a hole in the updrift breakwater) is completely protected from waves because it is inside of the inlet/harbour which works as a borrow area of sand where the dredge can take sand from. It gets almost as much sand as the updrift beach in the fixed bypass systems but require a dredge to get the sand from there anyway.

1.4.2. First Bypass Systems to be Operated

The first bypass kind of system was implemented almost 100 years ago: the first in Italy (Viareggio Harbour, 1936), Figure 1.6, and the second one in United States of America (Lake Worth Inlet, 1937), Figure 1.7.
1.4.2.1. Viareggio Harbour, Italy

Navigational improvements around Viareggio date from the Roman Empire and in 1913 an outer harbour was created with the construction of a breakwater. This resulted in an accretion of about 20 m/year in the updrift beach and a dramatic erosion downdrift. In 1936 220,000 m$^3$ were dredged from the outer harbour and discharged to the downdrift beach using a 60m pipeline representing the first application of a bypassing system (Sediments Management at Inlets and Harbors, 2003).

A lot of improvements were done since 1936 and at the moment the system in use consists of a flexible, mobile scheme and material can be dredged by floating suction dredges from the outer harbour, the large basin, the updrift beach or outside the harbour entrance. The current bypass system allows a rate of 1,100 m$^3$/hour of slurry with 20 % of sand (Sediments Management at Inlets and Harbors, 2003).

1.4.2.2. Lake Worth Inlet, United States of America

In 1918, the American local authorities began the work of dredging to create South Lake Worth Inlet, for both pleasure and commercial craft. As could be expected, the implementation of this inlet with the construction of two jetties created a barrier for the longshore sediment transport and erosion in the downdrift beaches started to be felt. This was of concern to the property owners in the area that started to take preventive measures. A property owner who owned a considerable length of shore spent 137,000 € to construct a seawall along the ocean frontage and after some years another 34,000 € to construct seven groins to support and protect the seawall from undermining. No effective beach was formed and South Lake Worth Inlet District decided to establish a sand pumping plant to bypass sand from updrift to downdrift beaches (Joseph M. Caldwell, 2010).

Almost 50,000 m$^3$ were pumped in the first year of operation (1937) and the effects of pumping operation were felt almost immediately along the shoreline downdrift of the inlet (Joseph M. Caldwell, 2010).

The operations stopped in 1942 due to war conditions but by that time the beach was completely restored. The operations restarted in 1945, after 3 years of severe erosion, with some improvements and continued the operations until now (Joseph M. Caldwell, 2010).

Fig 1.7 – Original Bypass System in South Lake Worth Inlet (Joseph M. Caldwell, 2010)
LONGSHORE SEDIMENT TRANSPORT

2.1. LONGSHORE SEDIMENT TRANSPORT

The natural cycle of sand, the one that we see on the beaches, starts on the river and only finishes when the grain of sand reaches a place where there is no influence of any action that can cause its movement (water or wind).

The longshore sediment transport is the amount of sand that moves from updrift to downdrift of the coast. In the Portuguese coast, where the swell comes mostly and more intensively from northwest, the sediment transport is dominantly from north to south.

This amount of sediments, which is in the order of a million of cubic meters, has multiple sources. If any physical barrier were constructed the sediments would come firstly from Spain, in the north part of Portugal, and then different volumes of sand would be added in different discharge points.

From north to south there are multiple sources of sand available (Magalhães, 1999):

- Minho River: 30,400 m$^3$/year;
- Lima River: 12,300 m$^3$/year;
- Cávado River: 8,400 m$^3$/year;
- Ave River: 12,600 m$^3$/year;
- Douro River: 329,200 m$^3$/year;
- Vouga River: 39,600 m$^3$/year;
- Mondego River: 79,900 m$^3$/year;
- Mira River: 16,500 m$^3$/year;
- Guadiana River: 220,200 m$^3$/year;
- Algarve Creeks: 41,900 m$^3$/year.

These are the most influential river mouths in Portugal that, without any physical restraint, would provide more than 3 million cubic meters of sand every year (Magalhães, 1999).

The river sediment transport can also be called sediment load. There are 3 types of sediment load (http://www.fondriest.com/environmental-measurements/parameters/hydrolgy/sediment-transport-deposition/):

- Bedload – portion of sediment transport that rolls, slides or bounces along the bottom of a waterway. It occurs when the force of the water flow is strong enough to overcome the weight and cohesion of the sediment. Bedload transport can occur during low flows.
(smaller particles) or at high flows (for larger particles). Approximately 5-20% of total sediment transport is bedload. In situations where the flow rate is strong enough, some of the smaller bedload particles can be pushed up into the water column and become suspended;

- Suspended Load – while there is often overlap, the suspended load and suspended sediment are not the same thing. Suspended sediment are any particles found in the water column, whether the water is flowing or not. The suspended load, on the other hand, is the amount of sediment carried downstream within the water column by the water flow;
- Wash load – The wash load is a subset of the suspended load. This load is comprised of the finest suspended sediment (typically less than 0.00195 mm in diameter). The wash load is differentiated from the suspended load because it will not settle to the bottom of a waterway during a low or no flow period. Instead, these particles remain in permanent suspension as they are small enough to bounce off water molecules and stay afloat. However, during flow periods, the wash load and suspended load are indistinguishable.

The sediment transport is not constant and so is an extremely difficult variable to determine. In addition to the changes in sediment load due to geology, geomorphology and organic elements, sediment transport can be altered by other external factors. The alteration to sediment transport can come from changes in water flow, water level, weather events and human influence.

2.1.1. EXTERNAL FACTORS THAT INFLUENCE THE SEDIMENT TRANSPORT

2.1.1.1. Water Flow

It varies with the water flow and its velocity like shown in Figure 2.1.

![Fig. 2.1 – Influence of water flow in sediment transport (fondriest.com)](image)

Water flow is the single most important element of sediment transport. The flow of water is responsible for picking up, moving and depositing sediment in a waterway. Without flow, sediment might remain suspended or settle out – but it will not move downstream.
2.1.1.2. Water Level and Weather Events

Sediment transport relies on water flow to move a load downstream. Water flow is variable, affected not only by slope of terrain, but by water level which, in turn, is influenced by precipitation or lack of it.

Most changes in water level are due to weather events such as rainfall. Precipitation causes water levels to initially rise, and then return to previous levels (base flow) over the course of hours or days. Rainfall, whether slight or heavy can affect water flow and sediment transport. The extent to which a weather event will influence sediment transport is dependent on the amount of sediment available. Snowmelt in a glaciated area will result in a high sediment load due to glacial silt. Heavy rainfall over an area of loose soil and minimal vegetation will create runoff, carrying loose particles into the waterway. Likewise, flooding will also pick up sediment from the local area. In fact, most of a waterway’s sediment load occurs during flood events.

Increased water level creates additional volume in a channel, and increases the hydraulic radius (cross-sectional area of a waterway). The increased hydraulic radius increases the discharge rate, regardless of whether or not flow is uniform or non-uniform. Increased flow will increase the stress on the bed, making it more likely for water flow to initiate sediment transport. The higher velocity also increases erosion rates as flow overcomes the shear stress of sediment.

Seasonal effects are also responsible for changes in water level and flow. Most seasonal changes are due to precipitation levels and events such as snowmelt. During low precipitation and low flow periods, sediment transport falls. During the peak of snowmelt, the sediment load can increase by a factor of 15 or more. Climate change can also play a role in sediment transport, as it affects both the timing and magnitude of floods and other weather events.

2.1.1.3. Human Influence

Anthropogenic factors, such as dams and altered land use will affect both the sediment load and sediment transport rate, Figure 2.2. Dams affect the water flow through complete detention or restricted channels. The restricted flow can cause the channel downstream of the dam to become “sediment-starved”, while the sediment load behind the dam builds up. A sediment-starved river will not be able to provide habitats for benthic organisms or spawning fish. The highly silted reservoir behind the dam may face issues of too much sediment, including changes in aquatic life and the potential for algal blooms. On the other side of the spectrum, when a dam release occurs, the flow rate downstream can dramatically increase. If the release is controlled, it can refresh the bed material, building bars and other habitat areas. An uncontrolled release or dam removal can result in flooding, carrying the released sediment further downstream than is needed.

Human land use, such as urban areas, agricultural farms and construction sites will affect the sediment load, but not the transport rate. These effects are indirect, as they require heavy rainfall or flooding to carry their sediment into the waterway. However, anthropogenic land use is one of the leading contributors to excessive sedimentation due to erosion and runoff. This increase occurs because “disturbed sites” (logging, mining, construction and farm sites) often expose or loosen top soil by removing native vegetation. This loose soil is then easily carried into a nearby river or stream by rainfall and runoff.
2.1.2. DOURO RIVER AND ITS IMPORTANCE

Douro River is the biggest source of sediments for the longshore sediment transport in Portugal (Magalhães, 1999). It is also the one that had more constructions in its waterway and consequently has the biggest deficit of sand moving downstream (an estimation of ~1 million cubic meters of sand per year).

Douro river mouth was strongly affected by the rising water level during heavy rainfall events, like can be seen in Figure 2.3. Many dams were constructed taking into account not only the electricity production but also the damages that the areas surrounding the mouth of the river were suffering every year.

This is a problem that no longer exists but its secondary effects produced a lack of sediment transport which in turn represents a deficit in nourishment of beaches that depend on the Douro River as a source of sand.

Aveiro and Figueira da Foz, mainly Aveiro, depend on the sand transported by Douro River to keep a dynamic transversal profile of the beach. With the waterfall of dams created in Douro River a lot of harmful effects are being felt in this part of Portuguese coast, which is actually the most endangered one in the entire country. A full analysis of this profile evolution over time and possible solutions for it is done in chapter 3.
2.1.3. SAND TRAPPING AND ITS CONSEQUENCES ALONG PORTUGUESE COASTLINE

Figure 2.4 contains the location of the biggest influences in sand trapping along Portuguese coastline.

2.1.3.1. Leixões Port Influence

Leixões is an Artificial Port 5 km north of Douro River Mouth. Douro River is, as written before, the biggest source of sand in Portuguese Coastline but, since the longshore sediment transport is mostly from north to south, any sand from Douro River reaches the adjacent beaches of this port. Consequently, sand dynamics in that surrounding area is low. Once the majority of the sand coming from north depends on Minho River and Spanish longshore sediment transport, both of them with low sand dynamics, sand trapped in Leixões Port updrift beach is nothing compared with Aveiro or Figueira da Foz Port.

Another important factor for the small longshore sediment transport in the northern part of Portugal is the nature of the beaches. Unlike the usually called West Coast of Portugal (between Aveiro and Peniche) where the beaches are all sandy, the northern part of Portugal is filled with rocky beaches where the sand transport along the coast is almost zero.
Figure 2.5 is from Foz, an area that represents half the distance between Douro River and Leixões Port.

![Image of a beach near Castelo do Queijo, Porto](guiadacidade.pt)

Fig. 2.5 – Beach near “Castelo do Queijo”, Porto (guiadacidade.pt)

2.1.3.2. Douro River and Aveiro Port Influence

Located 70 km south of Leixões Port, is a strip that represents one of the most dynamic parts of the Portuguese coastline. Being one of the most dynamic means that a lot of sand travels along this 70 km distance but the sand accumulated is very little.

Figures 2.6 and 2.7 represent two locations between Leixões and Aveiro Ports where sand accumulation is none and erosion effects are stronger year after year.
Furadouro is part of Ovar, a city with more than 55,000 habitants, which was responsible for the inadequate planning of the coastline. This inadequate planning forced a big investment in urban areas protection with the construction of adherent structures, groins and artificial nourishment of beaches.

Cortegaça, located 8 km north, is another poorly thought urban area which also forced the construction of adherent structures and groins in order to protect houses and public infrastructures.

Further south, as it gets closer to Aveiro Port updrift breakwater, the sand accumulation is huge and erosion problems are inexistent. Most of the beaches are unrecognisable since they got extremely bigger in the last 2 decades.
The coastline between Aveiro and Figueira da Foz Ports, excluding the 10 km immediately south of the Aveiro Port, where Costa Nova groin field, a groin field built to accumulate sand in such problematic coast some decades ago, is perfectly stable. Aveiro Port suffers from what can be called a natural bypass which allows sand to go through Port breakwaters and get back to the longshore sediment transport system further south.

Figures 2.8 and 2.9 are from two beaches between Aveiro and Figueira da Foz Ports. Vagueira beach is 8 km south of Aveiro Port and is strongly buffeted by beach erosion due to the inadequate planning of the coastline. Tocha Beach is 35 km away from Aveiro Port and perfectly represents the inexistent effect of beach erosion. This beach has completely different characteristics than Vagueira. It has a well protected dune system, there are no inadequate constructions destroying the natural environment of the beach and is far enough from Aveiro Port to not feel its effect as a longshore sediment transport barrier.
2.1.3.3. Figueira da Foz Port Influence

As it gets closer to Figueira da Foz Port, the erosion effects get close to zero. The most affected beach by the extreme sand accumulation is the one adjacent to the northern breakwater of Figueira da Foz Port, represented in Figure 2.10.

![Fig. 2.10 – Figueira da Foz River Mouth (where port is located) and consequences updrift and downdrift (Isa Alexandrina Lopes, 2017)](image)

On the other hand, and in the other side of the River Mouth, the erosion effects are strongly felt and urban areas have been constantly endangered. The 10 km of coastline south of Figueira da Foz Port, mainly Cova Gala beach, represented in Figure 2.11, are the worst cases.

![Fig. 2.11 – Effects of beach erosion downdrift of Figueira da Foz (portugalfotografiaarea.blogspot.com)](image)

The next southern sandtrap location in the Portuguese coastline is in Nazaré that, unlike those last studied locations, is a natural barrier of the longshore sediment transport.
2.1.3.4. Nazaré Promontory Influence

Nazaré has a peculiar characteristic which makes it different from any other place in the country and from most of the places in the entire world. In Norte Beach, north of Nazaré Promontory, and 500 meters out to sea, there is a canyon. This canyon extends for more than 170 km and reaches depths bigger than 5,000 meters.

This geomorphological accident causes major changes in the longshore sediment transport since it is an authentic sink for sand coming from north, which may prove the inexistence of abnormal accretions of sand in northern beaches.

On the other hand, the erosion downdrift of Nazaré Promontory is not perceived, mostly due to the diffraction effects provoked by the promontory which maintain the sand in the southern adjacent areas.

Figure 2.12 shows the northern beach of Nazaré village and its promontory.

![Fig. 2.12 – Nazaré Promontory and updrift beach (CCDRC, 2008)](image)

Figure 2.13 shows that, at the same time, downdrift beach also continues to increase decade after decade.

![Fig. 2.13 – Nazaré downdrift beach in 1950s and 6 decades later (cabo-carvoeiro-historico.blogspot.pt and portugaltours.com.pt)](image)
3

DREDGING AND EVOLUTION OF THE BEACH PROFILE

3.1. DREDGING SPECIFICATIONS IN AVEIRO AND FIGUEIRA DA FOZ PORTS

Dredging works are a usual thing in Portuguese coastlines, mainly in the adjacent areas of port infrastructures.

Dredging is carried out since the very first day of any single port in Portugal. First to the construction of breakwaters and establishment of the navigation channel and then during the period they are in operation. The proper functionality of a port and all its services require certain depths in certain areas because of the operations carried out in each place.

Fishing terminal, and its adjacent areas, is the less deep part of a port and the deepest ones are navigation channel, since all the ships, no matter how big is their draft, have to navigate in there, and then there are the Ro-Ro and Container terminals.

3.1.1. AVEIRO PORT

In Aveiro Port, depth goes from -2 m CD in small fishing port, to -13.2 m CD in the navigation channel. Aveiro Port is prepared to receive ships with a maximum draught of 10.5 m since the extension of the northern breakwater and deepening of the navigation channel in 2013. The navigation channel was deepened until -13.2 m CD and Container and Ro-Ro terminals were only until -12 m CD. This happens because the navigation channel is a very dynamic area of the port and has a higher tendency to siltation which requires bigger depths than the terminals area even though it receives ships with the same draft.

3.1.2. FIGUEIRA DA FOZ PORT

In Figueira da Foz the port is not divided into so many terminals. There is a commercial wharf which has no strict organization. All the length of the wharf is prepared for all kind of bulk material but usually there is an area for container, another one for dry bulk and another one for general cargo.

Figueira da Foz Port is not as deep as Aveiro Port since the work of navigation channel deepening is still to be carried out. Nowadays it goes from -4 m in the Marina until -8 m in the navigational channel.
and outer basin. Since the navigational channel was not deepen yet, it is extremely propitious to siltation and that has been the biggest challenge for Figueira da Foz Port Administration.

A geophysical and geological surveying is being developed by an external company to better understand the bottom of the navigation channel of Figueira da Foz Port. Its rocky characteristics are known and the difficulty to deepen a channel like this is a truly engineering challenge which involves explosions and removal of huge quantities of rocks.

Table 3.1 and Table 3.2, developed using Aveiro and Figueira da Foz Port Authorities documents, contain the necessary depths to be kept in all the terminals and areas of the two ports.

**Table 3.1 – Dredging depths in Aveiro Port**

<table>
<thead>
<tr>
<th>Location</th>
<th>Dredging depth (CD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lagoon Mouth and Outer Basin</td>
<td>-13.2 m</td>
</tr>
<tr>
<td>Northern Terminal</td>
<td>-10 m</td>
</tr>
<tr>
<td>Multi-Purpose Terminal</td>
<td>-12 m</td>
</tr>
<tr>
<td>Container and Roll-on Roll-off Terminal</td>
<td>-12 m</td>
</tr>
<tr>
<td>Dry Bulk Terminal</td>
<td>-12 m</td>
</tr>
<tr>
<td>Liquid Bulk Terminal</td>
<td>-12 m</td>
</tr>
<tr>
<td>Southern Terminal</td>
<td>-7 m</td>
</tr>
<tr>
<td>Fishing Port Basin</td>
<td>-5 m</td>
</tr>
<tr>
<td>Fishing Port</td>
<td>-4 m</td>
</tr>
<tr>
<td>Small Fishing Port</td>
<td>-2 m</td>
</tr>
</tbody>
</table>

**Table 3.2 - Dredging depths in Figueira da Foz Port**

<table>
<thead>
<tr>
<th>Location</th>
<th>Dredging depth (CD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lagoon Mouth and Outer Basin</td>
<td>-8 m</td>
</tr>
<tr>
<td>Outer Basin</td>
<td>-7 m</td>
</tr>
<tr>
<td>Manouvre basin and comercial wharf</td>
<td>-7 m</td>
</tr>
<tr>
<td>Marina</td>
<td>-4 m</td>
</tr>
<tr>
<td>Fishing Port</td>
<td>-6 m</td>
</tr>
<tr>
<td>“Bacalhoeiros” Dock</td>
<td>-5 m</td>
</tr>
</tbody>
</table>

No matter how deep is an area of the port, the draft of a boat allowed to navigate in there must be smaller in order to create some room for possible siltation which has been occurring very frequently.

Both in Aveiro and Figueira da Foz Ports, emergency dredging has been carried out due to extremely fast siltation of specific areas of the navigation channel, commercial wharf, etc.

That said, the maximum draft allowed for Aveiro Port is 10.5 m, even though no ship with a draft like that ever entered in Aveiro Lagoon Mouth.

In Figueira da Foz Port the maximum allowed draft is 6.5 m but usually, due to siltation of the navigational channel, the maximum allowed draft is only 5.5 m.
3.2. DREDGING RECORDS IN AVEIRO PORT

3.2.1. OVERALL ANALYSIS

Dredging records in Aveiro Port are registered since 1957 by Aveiro Port Authority, which provided all the information used in the following pages. In the first 20 years of registration, most of the dredged sediments were from navigational channels, multiple terminals and the entire lagoon system and were carried out in order to keep the perfect operational conditions of the port. All this sediments were then deposited south of the Port, directly on the beach or in offshore locations.

Since 1973 sand started to be traded to civil construction industry. Construction in Portugal had a boom at the end of 20th century and a huge amount of sand was required for hundreds of civil construction companies. Between 1973 and 2011 almost 13 million cubic meters of sand were dredged from the influence area of Aveiro Port to this purpose. Since 2011, due to the economic crisis and prohibition to trade more sand because of the erosion effects that were being felt in the entire Portuguese coastline, no more sand were dredged for commercial purposes in Aveiro Port.

Between 1988 and 2006 multiple dredging works were carried out for maintenance and expansion of port terminals in Aveiro Port area. Almost 9 million cubic meters of sand were dredged in that period and kept in a sandy ridge in port areas. Most of that sand was used for commercial purposes but nowadays more than 2 million cubic meters remain in that area.

Currently, a study is being carried out to remove that sand from port areas and use it to erosion mitigation purposes.

Since 2010 that dredging records are strictly controlled and was possible to develop a summary table regarding costs per year, per work and per cubic meter for Aveiro Port dredging works.

Apart from 3 exceptions:

- Reinforcement of dune system in 2011;
- Filling of an extremely deep hole in the navigation channel, which needs permanent control due to the danger it causes to adjacent structures, also in 2011;
- Sand placement immediately south of southern breakwater regarding the extension of northern breakwater work and due to an extremely severe winter (marked in Figure 3.1 in dark grey), in 2012 and 2013.

There are two main sand placement areas nowadays:

- Offshore location between depths – 2 and – 5 m CD, between groins 3 and 5 from Costa Nova groin field, marked in light grey in Figure 3.2;
- Offshore location, 6 miles away from the coast, with depths approximately – 40 m CD, marked in Figure 3.2 in black.

Figure 3.1 is a map of Aveiro Port adjacent areas and contains the dredging sources between 2010 and 2016. Figure 3.2 is a map containing the sand placement areas.
Fig. 3.1 – Dredging Sources in Aveiro Port (2010-2016)
Fig. 3.2 – Sand Placement Areas in Aveiro Port (2010-2016)
### 3.2.2. SUMMARY TABLE AND STATISTICAL ANALYSIS

Table 3.3 contains a summary of dredging records in Aveiro Port since 2010. The first column, apart from year of dredging also contains a colour code regarding dredging location. Aveiro Port has almost 10 different terminals, each one with different purposes and, consequently, different necessary depths depending on the vessels each one can take (detailed in Table 3.1). Thus, each one of terminal’s adjacent water areas will need more or less dredging operations, more or less often depending on its tendency to siltation.

Due to the number of different operations per year in different locations, the dredged area is divided by year. Figure 3.1 contains the colour code and the map regarding these dredged locations.

Sand placement areas were divided in 4 categories (colour classification) which are explained in Table 3.4.

<table>
<thead>
<tr>
<th>Year</th>
<th>Dredged Volume</th>
<th>m³/year</th>
<th>€/year</th>
<th>Cost per work (€)</th>
<th>€/m³</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010</td>
<td>50,000</td>
<td>279,000</td>
<td>1,048,780</td>
<td>147,500</td>
<td>2.95 €</td>
</tr>
<tr>
<td></td>
<td>20,000</td>
<td></td>
<td></td>
<td>59,000</td>
<td>2.95 €</td>
</tr>
<tr>
<td></td>
<td>50,000</td>
<td></td>
<td></td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>42,000</td>
<td></td>
<td></td>
<td>123,900</td>
<td>2.95 €</td>
</tr>
<tr>
<td></td>
<td>117,000</td>
<td></td>
<td></td>
<td>718,380</td>
<td>6.14 €</td>
</tr>
<tr>
<td>2011</td>
<td>175,000</td>
<td>250,000</td>
<td>428,750</td>
<td>122,500</td>
<td>1.70 €</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>8,750</td>
<td>1.75 €</td>
</tr>
<tr>
<td>2012</td>
<td>169,218</td>
<td>169,218</td>
<td>790,247</td>
<td>790,247</td>
<td>4.67 €</td>
</tr>
<tr>
<td></td>
<td>74,398</td>
<td>1,506,158</td>
<td>4,167,142</td>
<td>199,387</td>
<td>2.68 €</td>
</tr>
<tr>
<td></td>
<td>66,725</td>
<td></td>
<td></td>
<td>311,606</td>
<td>4.67 €</td>
</tr>
<tr>
<td></td>
<td>1,364,235</td>
<td></td>
<td></td>
<td>3,656,150</td>
<td>2.68 €</td>
</tr>
<tr>
<td></td>
<td>800</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2013</td>
<td>410,322</td>
<td>942,225</td>
<td>2,467,719</td>
<td>2,467,719</td>
<td>2.93 €</td>
</tr>
<tr>
<td></td>
<td>431,903</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>100,000</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2014</td>
<td>137,775</td>
<td>432,507</td>
<td>1,225,983</td>
<td>403,681</td>
<td>2.93 €</td>
</tr>
<tr>
<td></td>
<td>294,732</td>
<td></td>
<td></td>
<td>822,302</td>
<td>2.79 €</td>
</tr>
<tr>
<td>2015</td>
<td>82,339</td>
<td></td>
<td></td>
<td>229,726</td>
<td>2.79 €</td>
</tr>
<tr>
<td></td>
<td>160,998</td>
<td></td>
<td></td>
<td>766,350</td>
<td>4.76 €</td>
</tr>
<tr>
<td></td>
<td>180,849</td>
<td>562,441</td>
<td>1,957,970</td>
<td>504,569</td>
<td>2.79 €</td>
</tr>
<tr>
<td></td>
<td>36,342</td>
<td></td>
<td></td>
<td>172,988</td>
<td>4.76 €</td>
</tr>
<tr>
<td></td>
<td>101,913</td>
<td></td>
<td></td>
<td>284,337</td>
<td>2.79 €</td>
</tr>
</tbody>
</table>
Table 3.4 – Legend of Sand Placement Areas

<table>
<thead>
<tr>
<th>Sand Placement Areas</th>
</tr>
</thead>
<tbody>
<tr>
<td>6 miles away from the coast</td>
</tr>
<tr>
<td>Immediately south of southern breakwater</td>
</tr>
<tr>
<td>Depths between -2 and -5 CD</td>
</tr>
<tr>
<td>Extremely deep location in the navigation channel</td>
</tr>
<tr>
<td>Reinforcement of dune system</td>
</tr>
</tbody>
</table>

Statistical analysis of this summary table is developed using the following tables.

3.2.2.1. Volume per Sand Placement Area

The sand deposited in the location 6 miles away from coastline has to be deposited there because of its properties, mostly contaminated sand, and how they are inappropriate to mitigate beach erosion (both due to its chemical properties and gradation).

But those almost 3 million cubic meters deposited in depths between -2 m and -5 m CD (admitting that they are suitable for beach nourishment since the assumption is that all that sand eventually reaches the beach), if were used to beach artificial nourishment, considering the period of 7 years, would make up the average of more than 400,000 m³ trapped in the northern breakwater each year. And knowing that hundreds of thousands of Euros are spent by local municipalities every year in emergency works, usually before severe storms, pumping this sand to the beach instead of simply dump it in an offshore location would worth the cost difference.

The following figures are from February 2017, before, during and after the biggest storm registered during winter 2016/2017. Figure 3.4 shows a destroyed wooden walkway (which is replaced every single year and, this year, was destroyed when the first day of the storm reached the coast) in Vagueira Beach, even though local municipality built a sandy ridge to protect the structure. Figure 3.5 is from the southern beach of Vagueira (updrift of a groin) which got an intervention from the local municipality, which trucked 500 cubic meters of sand right before the storm.
The storm that reached the Portuguese coast in the beginning of February 2017 caused several material damages in multiple beaches along the Portuguese coastline. Aveiro is usually one of the worst affected each time a storm reaches Portugal.

This one was not an exception and Vagueira, the city which is below the high tide level, suffered from the storm, multiple materials were damaged and anything was done to anticipate it. In southern part of Vagueira beach a wooden walkaway was destroyed by the waves and a sandy ridge was only built the day after when it was obvious that, if anything was done, the beach club on top of the adherent structure would be destroyed, too.

Further south, represented in Figure 3.5, Labrego beach also suffered from devastation caused by the storm. Its beach club does not have an adherent structure protecting it and a sandy ridge was built the day before the storm. Even though, in the day after, most of the sand had already disappeared and one week later none of that sand was there.

These are the mitigation solutions for beach erosion carried out in Aveiro coastline and it is odd, to say the least, that after a year when more than 500,000 m$^3$ of sand were deposited in a location where, supposedly, beach erosion was being mitigated, situations like these continue to happen and emergency solutions still prevail.
3.2.2.2. Dredged Volume per Year and Respective Cost

By analysing Figures 3.6 and 3.7 one can conclude how proportional the correspondence between dredged volume and cost per year is. The huge difference between 2013 and the rest of the years is because of the deepening of navigation channel work. It involved the dredging of more than 1.5 million cubic meters only that year what have never been done in Aveiro Port (between 2010-2016). When dredging sand for commercial purposes were allowed, more than 1.5 millions of cubic meters were dredged during several years.
A graph with the direct comparison between volume and cost per year should not be developed since the dredging types are not always the same.

3.2.2.3. Type of Dredging and Cost per Cubic Meter

There are two different types of dredging methods used in Aveiro Port, like is represented in Figure 3.8, and Bucket Dredging is more expensive due to its complexity and its more meticulous way to be carried out.

Within Suction dredger, there are two different types:

- Trailer Suction Hopper Dredger (TSHD);
- Cutter Suction Dredger (CSD).
A TSHD is mainly used for dredging loose and soft soils such as sand, gravel, silt or clay. One or two suction tubes, equipped with a drag head, are lowered on the seabed, and the drag head is trailed over the bottom. A pump system sucks up a mixture of sand or soil and water, and discharges it in the ‘hopper’ or hold of the vessel. Once fully loaded the vessel sails to the unloading site. The material can be deposited on the seabed through bottom doors, or reclaimed by using the “rainbowing” technique. The material can also be discharged through a floating pipeline to shore, and used for reclaiming land (Jan De Nul GROUP, 2017).

In Aveiro Port the only way used to discharge the sand is by bottom doors. Techniques such as rainbow technique or through a floating pipeline to shore could be excellent alternative ways to sand bypass systems since, using these ways, the sand is deposited directly in the beach (using floating pipeline technique) or in locations closer to the coastline (using rainbow technique).

A CSD is equipped with a rotating cutter head, for cutting and fragmenting hard soils. The soil is sucked up by means of dredge pumps, and discharged through a floating pipeline and pipes on shore, to a deposit area. In some cases, the material is discharged into split hopper barges that are moored alongside the Cutter Suction Dredger. These split hopper barges unload the soil at the deposit area.

A CSD is a stationary dredger, i.e. it does not ‘sail’ when dredging. During dredging the vessel remains on the same location, secured by a spud lowered in the seabed; by means of winches and anchors, the dredger swings sideways and the cutter head cuts and removes the soil (Jan De Nul GROUP, 2017).

Figures 3.9 and 3.10 contain images from the two different types of suction dredger.
Regarding Bucket dredging there are three different types of possible equipment and method:

- **Backhoe Dredger (BHD)**, in Figure 3.11;
- **Grab Dredger (GD)**, in Figure 3.12;
- **Bucket Ladder Dredger (BLD)**, in Figure 3.13.

A BHD is basically a pontoon equipped with a hydraulic excavator. To stabilize and secure the pontoon three spuds are installed. The excavator will excavate the soil, and discharge it into a split hopper barge that is moored alongside the pontoon. The split hopper barge unloads the soil at the deposit area (Jan De Nul GROUP, 2017).

The BLD use a series of buckets that are mounted to a wheel, which then using mechanical means pick up the sediments. They can be used for wide variety of materials including soft rock material and are powerful enough to rip out the corals as well. But because of their low production, high level of noise and the need for anchor lines, their use has hugely diminished in the recent times (Marina Insight, 2017).

A revolving crane, fitted with a grab, placed on a hopper vessel or pontoon is known as a GD. As the name suggests, it picks up the sediments at the seabed with a clam grabbing motion and discharges the contents. Often used for excavating bay mud it also is useful to pick up clays and loose sand (Marina Insight, 2017).
• Trailer or Cutter Suction Dredger;
• Grab Dredger.

Trailer or Cutter Suction Dredger are mostly used when the required depths are bigger and the material to dredge is thinner. It is used in the navigation channel, lagoon mouth, outer basin and terminals where the depths go until -13.2 m.

Grad Dredger is used when the required depths are smaller and material dimension is higher. In Fishing Port and Small Fishing Port, where the depths can be as small as -2 m CD, a less intrusive method is necessary because a too deep Port, when is not necessary, can also be dangerous both to ships and to existent adjacent structures.

![Bucket Ladder Dredger](dsboffshore.com)

**3.2.2.4. Dredged Volume per Month**

![Dredged Volume per Month (2010-2016)]

In the first months of the year, due to the lay of bivalves (between January and April), is prohibited to dredge to the erosion mitigation discharge location. Months between April and August, due to the
usually calm weather and wave conditions, would be the best months for dredging operation since the sand would most probably reach the coastline and contribute to erosion mitigation. But these summer months also have some constraints due to the bathing season and the interference that dredging can have in water quality conditions.

In September the winter wave season starts and the conditions for dredging operations get worse every month till February. If sand is discharged in an offshore location during summer months, with low energy waves, the probability of reaching the coastline is high but during winter months and high energy wave periods the sand will mostly go straight to south and only stops if a physical barrier exists. That is why so many hundreds of thousands of cubic meters get trapped in Aveiro updrift breakwater every single year.

### 3.3. Dredging Records in Figueira da Foz Port

#### 3.3.1. Overall Analysis

Dredging records of Figueira da Foz Port Authority are only accurately and strictly collected since 2002 and were also provided by Aveiro Port Authority since the two Port Authorities merged in 2009.

Most of dredging operations between 2002 and 2006 had commercial purposes as their final destination. In this period, almost 2 million cubic meters of sand were dredged from Figueira da Foz River mouth and used for trading. Nowadays, sand dredged from this area of the Port is used to "erosion mitigation" since it is deposited in the location designated as such. It means that 2 million cubic meters of sand that would naturally reach Portuguese coastline and replace the sand in beaches never reached their final destination.

Since Figueira da Foz River mouth represents a highly dynamic system concerning sand movement, since 2006 that dredging operations have been carried out to maintain the good navigational conditions of the Port. From the 3.7 million cubic meters of sand dredged since 2006, 2.6 million cubic meters were deposited in the offshore location between depths -2 m and -8 m CD. The efficiency of this location in the erosion mitigation stems from the fact that the depth -2 m CD, in the part of the coastline in which the sand placement area is, is 150 meters from the coastline (high tide level) and the depth -8 m CD is 1000 m from the coastline (by the analysis of beach profile evolution developed further in this chapter).

Deposit sand in a depth of -2 m CD or in -8 m CD is a completely different task, regarding many variables. Deposit sand in a depth of -2 m CD requires a lot of experience from the dredger operator since the operation has to be carried out only during high tide and with extra care since the water depth, even during high tide, is not that big. That said, it will consequently involve higher operational costs. The easiest way to carry out a dredging operation like this, since the contract stipulates a huge area of sand placement, is to place the sand in the highest and, consequently, easiest area allowed.

Figure 3.15 contains the track of the last dredging operation carried out in Figueira da Foz Port.
Considering this marine traffic screen shot taken on 7th of June 2017, during a dredging operation in Figueira da Foz Port, the control of dredging placement area was done. By analysing the beach profile of that area, it was determined that depths between -2 and -8 m CD, where somewhere between 150 m and 1,000 m from the coastline. That said it was expected that some of the sand is placed in depths -2 and another part in depths somewhere between -2 and -8 but that is not the case. Dredging companies have been charging prices per cubic meter of sand dredged lower and lower in the past few years and, obviously, will deposit sand in the easiest place of all which is as far from the coast as permitted.

Sand placement in areas of depths -2 m CD, due to its proximity to the coast would certainly mitigate beach erosion and would be a great contribute to this problem. But if no control is carried out, dredging companies will always try to get as much money as possible and, consequently, lose work quality.

Like in Aveiro Port case, dredging records in Figueira da Foz were strictly determined since 2010 and Table 3.5 contains a detailed analysis of those records (regarding costs per year, per cubic meter and dredged volume).

The commonly dredged locations in this period were:

- Fishing Port with sand placement in depths of 40 m CD;
- River Mouth, Outer Basin and Multipurpose Terminal adjacent areas with sand placement in depths between -2 m and -8 m CD.

Figure 3.16 contains dredge locations and sand placement areas in Figueira da Foz Port.
Fig. 3.16 – Dredging Sources and Sand Placement Areas in Figueira da Foz Port (2010-2016)
3.3.2. Summary Table and Statistical Analysis

Table 3.5 resumes 7 years of dredging operations in Figueira da Foz Port. Figueira da Foz Port is quite smaller than Aveiro’s and therefore dredging records are simpler and clearer. There are only two sand placement areas to consider: 6 miles away from the coast and in an area with depths between depths -2 and -8 m.

Dredged locations are only 5: River Mouth, Outer Basin, Multipurpose Terminal adjacent areas, Fishing Port and “Bacalhoeiros” Dock, and were classified using a color code. The used color code is detailed in the map of Figure 3.16 and respective legend is in Table 3.6.

Table 3.5 - Dredging records in Figueira da Foz Port Adjacent Areas

<table>
<thead>
<tr>
<th>Year</th>
<th>Dredged Volume and Sand Placement Area</th>
<th>Dredged Location</th>
<th>m³/year</th>
<th>€/year</th>
<th>Cost per work (€)</th>
<th>€/m³</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010</td>
<td>50,000</td>
<td></td>
<td>115,800</td>
<td>374,250</td>
<td>249,500</td>
<td>4.99</td>
</tr>
<tr>
<td></td>
<td>25,000</td>
<td></td>
<td></td>
<td>124,750</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>40,800</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2011</td>
<td>112,000</td>
<td></td>
<td>410,000</td>
<td>1,077,400</td>
<td>76,000</td>
<td>2.00</td>
</tr>
<tr>
<td></td>
<td>38,000</td>
<td></td>
<td></td>
<td>358,800</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>120,000</td>
<td></td>
<td></td>
<td>418,600</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2012</td>
<td>200,957</td>
<td></td>
<td>300,957</td>
<td>983,445</td>
<td>723,445</td>
<td>3.60</td>
</tr>
<tr>
<td></td>
<td>100,000</td>
<td></td>
<td></td>
<td>260,000</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>17,783</td>
<td></td>
<td>292,449</td>
<td>780,717</td>
<td>64,019</td>
<td>3.60</td>
</tr>
<tr>
<td>2013</td>
<td>90,000</td>
<td></td>
<td></td>
<td>267,000</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>19,037</td>
<td></td>
<td></td>
<td>68,533</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>165,629</td>
<td></td>
<td></td>
<td>381,165</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2014</td>
<td>58,000</td>
<td></td>
<td>275,000</td>
<td>873,310</td>
<td>259,200</td>
<td>4.47</td>
</tr>
<tr>
<td></td>
<td>110,000</td>
<td></td>
<td></td>
<td>311,300</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>107,000</td>
<td></td>
<td></td>
<td>302,810</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2015</td>
<td>240,733</td>
<td></td>
<td>423,000</td>
<td>1,197,090</td>
<td>681,274</td>
<td>2.83</td>
</tr>
<tr>
<td></td>
<td>182,267</td>
<td></td>
<td></td>
<td>515,816</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>200,000</td>
<td></td>
<td>360,000</td>
<td>866,800</td>
<td>566,000</td>
<td>2.83</td>
</tr>
<tr>
<td></td>
<td>160,000</td>
<td></td>
<td></td>
<td>300,800</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 3.6 – Legend of dredging locations

<table>
<thead>
<tr>
<th>Dredging Locations</th>
</tr>
</thead>
<tbody>
<tr>
<td>River Mouth and Outer Basin</td>
</tr>
<tr>
<td>Multipurpose Terminal Adjacent Areas</td>
</tr>
<tr>
<td>Fishing Port</td>
</tr>
<tr>
<td>“Bacalhoeiros” Dock</td>
</tr>
</tbody>
</table>
Table 3.7 - Legend of sand placement areas

<table>
<thead>
<tr>
<th>Sand Placement Areas</th>
</tr>
</thead>
<tbody>
<tr>
<td>6 miles away from the coast</td>
</tr>
<tr>
<td>Depths between -2 and -8 CD</td>
</tr>
</tbody>
</table>

Statistical analysis of this summary table is developed using the following tables.

3.3.2.1. Volume per Sand Placement Area

Like in Aveiro Port situation, also in Figueira da Foz Port, the sand that is discharged in the location 6 miles away from the coast is because of its contamination. That is sand dredged from certain locations of the Port which have not enough quality to be used for erosion mitigation ends.

On the other hand, more than 1.75 million cubic meters of sand were discharged in depths between -2 and -8 m CD which are supposedly to mitigate beach erosion downdrift of Figueira da Foz Port. This location is almost 1 km south of downdrift breakwater of Figueira da Foz Port and the immediately south beach of southern breakwater is one of the most affected areas by wave action and the extreme lack of sand existing there. That said, a solution to fill this lack of sand is very urgent. A fixed sand bypass system is considered an excellent solution for this problem but some others sand bypass systems can also fill this lack of sand reaching that part of the coast, as will be studied in chapters 5 and 6.

In Aveiro Port, the volume of sand, discharged in the defined area of sand discharging, in the last 7 years was enough to fill the sand trapped in the updrift breakwater during all those years. That does not happen in Figueira da Foz but it does not mean that sand is not being dredged from the updrift part of the Port. It just happens because Figueira da Foz Port area is not as big as Aveiro’s.

The biggest operation problem of Figueira da Foz Port is how easily siltation occurs in Figueira da Foz River Mouth. An average of 500,000 m³ of sand get trapped by the updrift breakwater but another equal portion of sand bypasses the Port entrance every year and a significant proportion of that sand accumulates at the entrance and requires constant and some emergencies dredging works.
Several marine accidents happened in Figueira da Foz River Mouth in the last few years and some of them did not even happen with extreme wave conditions. The siltation of the river mouth can happen from one month to another and the navigational conditions get very dangerous.

Figure 3.18 is from a maritime accident in October 2015 which happened right in Figueira da Foz River Mouth. This accident happened in a day when the maximum wave height was only 4 m high and waves were not supposed to break in a River Mouth during a storm like that.

Siltation of the navigation channel in Figueira da Foz River Mouth is common and a sand bypass system would bring positive effects regarding this problem.

In Tweed River, where a sand bypass system is operating since 2001, there was an extremely big difference of necessary dredge volumes of River Mouth before and after sand bypassing system started to operate.

Table 3.8 represents the annual dredged volumes of Tweed River Mouth during the year before sand bypass system started to operate and then 16 years of its operation.

<table>
<thead>
<tr>
<th>Year</th>
<th>2000</th>
<th>2001</th>
<th>2002</th>
<th>2003</th>
<th>2004</th>
<th>2005</th>
<th>2006</th>
<th>2007</th>
<th>2008</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dredged Volume (t)</td>
<td>532,517</td>
<td>289,972</td>
<td>240,129</td>
<td>230,892</td>
<td>169,926</td>
<td>199,059</td>
<td>200,298</td>
<td>0</td>
<td>198,979</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Dredged Volume (t)</td>
<td>0</td>
<td>0</td>
<td>200</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>41,938</td>
</tr>
</tbody>
</table>
The dredged volume declined rapidly and consequently, accidents that were also used to happen never happened again, vessels can enter through the river entrance in most of weather and wave conditions and costs were reduced significantly.

3.3.2.2. Dredged Volume per Year and Respective Cost

By analyzing Figures 3.19 and 3.20, which contain dredging volumes and corresponding costs per year, in the last seven years, is conspicuous the proportionality between the annual dredged volume and costs.

The only exception is between 2013 and 2014. In 2014, a lower volume of sand was dredged and the cost increased. Since this dredging works are performed through public contracts, the prices will always depend on competition existing at a certain time and if the usually cheapest company is not available for a work the usually more expensive one can get the contract.
Like in Aveiro Port situation, it would be wrong to directly compare annual dredged volumes and costs since there are two types of dredgers which are used for different types of works.

### 3.3.2.3. Type of Dredging and Cost per Cubic Meter

A full analysis of different types of dredgers and ways of operating is developed in 3.2.2.3. regarding Aveiro Port dredging summary table and statistical analysis. Type of dredging used and its costs is represented in Figure 3.21.

### 3.3.2.4. Dredged Volume Per Month

![Dredged volume per Month (2010-2016)](image)
The existing restrictions for Aveiro Port also apply in Figueira da Foz Port, which has its dredging distribution represented in Figure 3.22. The beginning of the year is conditioned by the lay of bivalve, then there is the bathing season and in the end of the year winter wave season starts. All this rules left a maximum of 2 months for free dredging operations during the year, what is completely impossible for the proper functioning of a port. In Figueira da Foz, due to extremely high siltation rate of navigation channel and River mouth, emergency dredging operations has to be allowed during all year long.

3.4. AVEIRO AND FIGUEIRA DA FOZ PORT INFLUENCE IN THE ADJACENT AREAS

3.4.1. AVEIRO PORT INFLUENCE

Aveiro Lagoon Mouth changed a lot since the two breakwaters were constructed with the implementation of the Aveiro Port. The inlet used to change a lot and consequently the sand was kept moving freely from updrift to downdrift sides of the inlet. Since the breakwaters were built, a huge sand trap was automatically generated and millions of cubic meters of sand were maintained in there for more than 200 years now. Figures 3.23 and 3.24 clearly represent how different and unrecognized the updrift side of the inlet is from 56 years ago till 2014, right after the extension of the updrift breakwater.

![Fig. 3.23– Aveiro Port after 1958 (www.prof2000.pt)](image1)
![Fig. 3.24 – Aveiro Port in 2014 (Francisco Piqueiro)](image2)

The updrift rubble-mound breakwater was extended 700 meters since that time and even though the updrift beach did not exaggeratedly accreted the problem is that the sand never went to the downdrift side of the inlet like it was before. That created a huge coastline recession each time the breakwater was extended:

- In 1936 the updrift breakwater was extended to the sea, getting 690 m;
- In 1958 the downdrift breakwater was built with 780 m;
- In 1987 the updrift breakwater was extended more 500 m;
- In 2013 the updrift breakwater was extended more 200 m, as it is nowadays.

The updrift beach of Aveiro Port breakwaters never stopped to accumulate sand and it seems full capable to trap even more. On the other hand, the downdrift beaches seem to be more endangered year by year. The first beach south of the southern breakwater has been strongly battered by severe storms with enormous significant wave heights. But, due to the diffraction effect which happens in this beach, as can be seen in the bottom left part of Figure 3.24, the sand tends to accumulate in the adjacent area of this breakwater and the most affected beaches are the ones further south.
The biggest problems are the local conditions and geographical characteristics of the southern beaches. The most problematic one, Vagueira Beach, is located below the High Tide level and has an adherent structure along its entire coastline to prevent the waves from reaching the urban area and consequently destroy houses and their possessions. But the problem is not only this one. As can be seen in the top right part of Figure 3.23, there is the ocean, then there is land and after that there are multiple channels which are all part of the huge Aveiro Lagoon system. Imagining that the waves could go through the adherent structure in Vagueira Beach, and then reach the Aveiro Lagoon system, in addition to the destruction of an entire urban area, it would destabilise the Lagoon system and its ecosystem.

A complete study of the coastline evolution is developed further in this chapter.

3.4.2. FIGUEIRA DA FOZ PORT INFLUENCE

Figueira da Foz is the second big city of Coimbra district and has 28,000 inhabitants. Back in 1950s it was known as the queen of Portuguese beaches since it was one of the busiest beaches in the country.

But when in 1966 the inlet was established, with the construction of the two rubble-mound breakwaters, the updrift beach of Figueira da Foz River Mouth, like is shown in Figure 3.25, completely changed. In the first 10 years after the establishment of the river inlet more than 30 meters of sand accumulated in the updrift beach every year and 7 meters per year 3 km north of the updrift breakwater.

In contrast, the downdrift beach started losing 30 meters of coastline every year. This started to be a big concern for the local municipalities since the downdrift area of the inlet contemplates multiple urbanized areas, buildings near the coastline and consequently endangered people and houses.

To mitigate this problem several operations were carried out:

- Artificial nourishment (300,000 m$^3$) of the downdrift beaches (50 meters south of the southern breakwater) between 1973 and 1976, with sand coming from the dredging of the navigation channel;
- Groins and adherent structures in the downdrift beaches.

In 2008 the updrift breakwater was extended in 400 m in order to create bigger depths in the navigation channel and to prevent emergency dredging of the channel. Emergency dredging is still necessary sometimes since the reconfiguration of the breakwater was not that effective.
Figueira da Foz has nowadays the biggest urban beach in Europe, it completely lost its identity and the usage and the reputation as it was before no longer exist. As seen in Figure 3.25 there is a huge tower with a clock in the top that was the symbol of the city (even the beach is known as “Clock Beach”) and nowadays, with such an enormous amount of sand, it is not relevant anymore. That beach garden in the most recent picture was a try to give a new life to the beach as it lost most of its life during recent years. It is now completely abandoned and remiss since it did not have the expected success.

3.5. Profiles Location

3.5.1. Aveiro Port Adjacent Areas

In 2013, when the northern breakwater of Aveiro Port was extended in order to create navigational conditions in the navigation channel as good as possible. It allowed boats with a bigger draft to perfectly navigate in Aveiro Port navigation channel and make it more competitive against the other Ports in Portugal, mainly Leixões because is the major one in the surrounding area.

The environmental impact study, to ensure that the influence of the 200 m extension to the updrift breakwater in the longshore sediment transport would be controlled and minimized if major problems were noticed, required Aveiro Port Authority an annual control of the beach profile in the influence area. This adjacent areas go from 1 km north of the updrift breakwater (2 profiles in São Jacinto Beach) until 10 km south of the downdrift breakwater and comprises a coastline with 7 groins, with 2 of them L shaped with respectively adherent structure and another adherent structure.

These different structures strongly influence beach profiles either in a positive or a negative way. Updrift of each one of the 7 groins there is a significant accumulation of sand but the downdrift side suffers from localized erosion like the Figure 3.26 represents.

The report developed by Aveiro Port Authority every November since 2009 consists of 12 different profiles separated by 1 km along the coastline. After a rigorous compilation of the 8 years profiles (2009, 2010, 2011, 2012, 2013, 2014, 2015 and 2016), 12 comparative graphs were developed in order to understand how significant the accretion is in the updrift side of the port and how big is the erosion effect in the downdrift side. An important note is that there are a lot of people living in the downdrift area of the port. There are urbanized areas, schools, restaurants and above all there are thousands of people depending on the beach health to keep their lives together. Hostels have been built in this area, lots of new buildings and tourist sites born in the last few years, considering that right measures would be taken to ensure the healthy beaches that would exist if the longshore sediment transport was not constantly stopped.
In Figure 3.27 the location of the 12 different beach profiles in Aveiro coastline is marked as well as the depth of closure for each one of those profiles. Due to the periodic necessity to dredge the navigation channel and its surrounding area in order to maintain certain depths, in profile 3 and 4 it is quite hard to perfectly determine the depth of closure and, consequently, the distance from coastline until the location of depth of closure is huge in those profiles.

Fig. 3.27 - Beach profiles Location and Respective Depth of Closure – Aveiro
3.5.2. FIGUEIRA DA FOZ PORT ADJACENT AREAS

Like it was done when the updrift breakwater of Aveiro Port was to be built, also in Figueira da Foz, the Port Authority had to carry out a regular check of beach profiles in the surrounding area of the Port.

The extension of the breakwater was done in 2008 and the environmental impact study predicted the monitoring of 15 beach profiles along the coastline of Figueira da Foz. They start in Buarcos, the northern boundary of Figueira da Foz city, and go until Leirosa Beach, 7 km south of the downdrift breakwater.

Immediately south of the downdrift breakwater there is Cabedelo Beach which comprises a couple of café and restaurants, surf schools and a campsite, beyond Port infrastructures. That is the closest area to the downdrift breakwater but it is not the most critical one. Some kilometres south, because there is an endangered hospital built right behind the dunes, as seen in Figure 3.28, a groin field was implemented to protect this important infrastructure. 5 groins are implemented but when a big storm hits the coastline the worst is always expected. A couple of emergency actions were carried out in the last few years but no permanent one was implemented. The last one consisted of destroying the hydraulic dune to fortify the dune system. As is known, the hydraulic dune is the first protection against wave action and this attempt to protect the hospital could not be worst.

South of this groin field there are a couple more groins: one in Costa de Lavos Beach and another in Leirosa Beach. Close to each one of these groins there are urban areas that already existed when the Port breakwaters were built. Since it caused erosion downdrift there was the need to protect those people and their houses. These groins were the best alternative for a permanent protection since they cause accumulation of sand in the updrift side and, because they are separated by less than 1.5 km, they act like a small groin field, maintaining a large shoreline strip reasonably safe.

Fig. 3.28 – Hospital location and its vulnerability to wave action (Google Earth, May 2017)
Figure 3.29 contains the location of each beach profile and respective depth of closure.
3.6. Accumulated Volume of Sand in the Updrift Side of the Port

3.6.1. Longshore Sediment Transport in Portugal

A lot is written about evolution of beach profiles and the tendency is to determine a fix value for how much sand drives the Portuguese littoral every year but this seems quite unreliable.

The littoral drift is influenced by dozens of different factors which do not have a defined pattern neither for a year nor for a decade. The precipitation in Portugal does not have a fixed period like in many other countries in the world, the dams do not discharge the same volumes of water every single year and consequently the amount of sand that reaches the river mouths is variable from one year to another. The height of the waves, another great influencer of longitudinal sand transport, can be very different every single year. There are winters like 2013/2014 in which dozens of huge swells reached the Portuguese coast but there are also winters like 2016/2017 in which any extreme swell (Hs>7.5 m) happened.

The only two unvarying factors are:

- Swell direction – mainly from Northwest;
- Wave season – oceanic winter from November to March.

This greatly facilitates the task of sand accumulation calculation once the littoral drift is in its vast majority from North to South and small or inexistent swells happen during several months of the year (March to September) which is called the oceanic summer.

The wind is not extremely powerful and direction variable like in Monsoon areas (Bay of Bengal for example, one of the studied locations in the literature review) therefore the wind influence in the longitudinal sediment transport can be ignored.

3.6.2. Calculation Methods

Considering the lack of rigor that there is to ground longitudinal sediment transport calculation in add and subtract a couple of factors like normal river sediment flow and sand coming from northern part of Portugal, it was decided to use beach profile comparison since 2009 to calculate, using what is considered to be a reliable way, the accumulated sand volume updrift of northern breakwaters of Aveiro and Figueira da Foz ports.

Beach profiles between 2009 and 2010, 2010 and 2011 and so on since 2015-2016 were compared, calculating the accreted and eroded area (using software AutoCAD), multiplying those areas by the distance between the two contiguous profiles, and finally making an extrapolation between the southern profile and the northern breakwater. In Aveiro’s situation, were considered the profiles P₁ and P₂ (the other profiles are represented in appendixes 2 for Figueira da Foz and 4 for Aveiro). Profiles area located 1000 m from each other and Profile P₂ is located 190 m from the northern breakwater. According to this, the calculation method is as Table 3.9:

<table>
<thead>
<tr>
<th>Period</th>
<th>Prof.</th>
<th>Silt. (m³)</th>
<th>Desilt. (m³)</th>
<th>Bal. (m³)</th>
<th>Dist. between profiles</th>
<th>Dist. between P₂ and northern breakwater</th>
<th>Balance of sand in northern breakwater</th>
<th>Vol. (m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>P₁</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>P₂</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1000</td>
<td>190</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
In Figueira da Foz, since there are 3 Profiles north of the northern breakwater, only the 2 closest ones were used in the calculation of sand accreted updrift. The distance between Profile P2 and Profile P3 is 1,000 m and 60 m separate the Profile P3 and the northern breakwater. Table 3.10 shows how the calculation was carried out with more precision:

Table 3.10 - Calculation method in Figueira da Foz

<table>
<thead>
<tr>
<th>Period</th>
<th>Prof.</th>
<th>Silt. (m³)</th>
<th>Desilt. (m³)</th>
<th>Bal. (m³)</th>
<th>Dist. between profiles</th>
<th>Dist. between P3 and northern breakwater</th>
<th>Balance of sand in northern breakwater</th>
<th>Vol. (m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Across the coastline (m)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>P2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>P3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>60</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The balance of sand in northern breakwater was determined doing an extrapolation between the closest profile to the northern breakwater and considering the distance between that profile and the breakwater.

3.6.3. AVEIRO PORT

In the last 7 years, Aveiro Port updrift beach has an accumulation or loss of sand like represented in Table 3.11.

Table 3.11 – Sand balance updrift of Aveiro Port

<table>
<thead>
<tr>
<th>Period</th>
<th>Sand balance updrift (m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2009 - 2010</td>
<td>- 1,774,100</td>
</tr>
<tr>
<td>2010 - 2011</td>
<td>+ 575,685</td>
</tr>
<tr>
<td>2011 - 2012</td>
<td>+ 486,385</td>
</tr>
<tr>
<td>2012 - 2013</td>
<td>- 294,060</td>
</tr>
<tr>
<td>2013 - 2014</td>
<td>- 725,365</td>
</tr>
<tr>
<td>2014 - 2015</td>
<td>+ 1,092,130</td>
</tr>
<tr>
<td>2015 - 2016</td>
<td>+ 23,125</td>
</tr>
</tbody>
</table>

Aveiro Port situation is quite unstable. Considering only the period between 2010 and 2012 it would seem that a volume of 500,000 m³ was being trapped in the northern breakwater of Aveiro every year. But, apart from that period, there was no other regular period of sand accumulation in the studied period.

Since there are extreme differences from some periods to another it was decided to collect data from possible reasons for this completely random accretion/erosion of the updrift beach of Aveiro Port. Aveiro Port Authority developed a table consisting of dredging reports since 1957 which was used to justify this highly sand dynamical system in the updrift part of Aveiro Porto. The dredging reports were not enough and wave data since 2011 was also used to better understand the influence of these two factors in the quantity of sand trapped each year in São Jacinto Beach.
Table 3.12 was developed cross-checking information from historical dredging records and wave data, on the studied years (2009 – 2016 for dredging and 2011 – 2016 for wave data records).

Table 3.12 – Silting, Desilting and their possible reasons

<table>
<thead>
<tr>
<th>Period</th>
<th>Sand balance updrift</th>
<th>Relevant Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>2009 - 2010</td>
<td>- 1,774,100</td>
<td>• 1 million m$^3$ were dredged from Aveiro Port Mouth between April and October 2009.</td>
</tr>
<tr>
<td>2010 - 2011</td>
<td>+ 575,685</td>
<td>• Unusual calm year (48 minor and 6 severe storms);</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• 175,000 m$^3$ of sand were dredged from updrift part of Aveiro Port but it seems that it didn’t influence the sand trapping.</td>
</tr>
<tr>
<td>2011 - 2012</td>
<td>+ 486,385</td>
<td>• Unusual calm period (61 minor and 8 severe storms)</td>
</tr>
<tr>
<td>2012 - 2013</td>
<td>- 294,060</td>
<td>• Several dredging works were done in the surrounding areas (1.5 million m$^3$) due to the extension of the northern breakwater;</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• 92 minor storm and 19 severe storms.</td>
</tr>
<tr>
<td>2013 - 2014</td>
<td>- 725,365</td>
<td>• Extremely severe winter (92 minor and 36 severe storms);</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Highly dynamic sand transport due to the northern breakwater extension and navigation channel works.</td>
</tr>
<tr>
<td>2014 - 2015</td>
<td>+ 1,092,130</td>
<td>• Relatively calm year after two intense years in terms of wave energy (87 minor and 7 severe storms);</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• No dredging in the surrounding area of northern breakwater.</td>
</tr>
<tr>
<td>2015 - 2016</td>
<td>+ 23,125</td>
<td>• High number of severe storms (59 minor and 12 severe storms;</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• No dredging in the surrounding area of northern breakwater.</td>
</tr>
</tbody>
</table>

Even though the sand balance is very unstable in Aveiro Port situation, for the further calculations in this thesis, the considered bypass rate will be 400,000 m$^3$ of sand per year.

3.6.4. FIGUEIRA DA FOZ PORT

Table 3.13 - Sand balance updrift of Figueira da Foz Port

<table>
<thead>
<tr>
<th>Period</th>
<th>Sand balance updrift (m$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010 - 2011</td>
<td>+ 436,238</td>
</tr>
<tr>
<td>2011 - 2012</td>
<td>+ 436,238</td>
</tr>
<tr>
<td>2012 - 2013</td>
<td>+ 436,238</td>
</tr>
<tr>
<td>2013 - 2014</td>
<td>+ 436,238</td>
</tr>
<tr>
<td>2014 - 2015</td>
<td>+ 512,550</td>
</tr>
<tr>
<td>2015 - 2016</td>
<td>+ 586,620</td>
</tr>
</tbody>
</table>

* Considering that there are only one report in 2010 and another one in 2014 and that the same amount of sand accumulates on the updrift beach every year, dividing 1,744,950 per four, gives an annual volume of 436,237.5 m$^3$ being trapped in Figueira da Foz Updrift Beach.
The situation in Figueira da Foz is completely different from Aveiro’s even though the swell that hits Figueira da Foz coastline is pretty much the same that hits Aveiro. Since 2002 (year that dredging reports in Figueira da Foz Port started to be strictly reported) that both mouth and navigational channel of Figueira da Foz area annually dredged in a quantity never below 100,000 m$^3$. But even though the volume of sand accumulated in the updrift beach of Figueira da Foz Port is always around 500,000 m$^3$. That said, the volume to bypass in Figueira da Foz Port, regarding further calculations, will be considered as 500,000 m$^3$/year.

3.6.5. BEACH PROFILE EVOLUTION OF AVEIRO PORT UPDRIFT BEACH

To have a clearer idea of how the beach profile has evolved in the last 7 years, Figure 3.30 and Figure 3.31 represent the beach profile evolution in the updrift beach of Aveiro Port.

![Image of beach profile evolution](image-url)

With also a couple of periods in which the coastline retreated, never more than 50 meters, it is notorious that the tendency is that the updrift beach of Aveiro Port will get bigger year after year. To better understand the retreat or advancement of the coastline in this specific location around Aveiro Port, Table 3.14 represents the retreat or advancement of this Profile over the studied period.

<table>
<thead>
<tr>
<th>Table 3.14 – Retreat/advancement of the coastline in Profile 1, Aveiro</th>
</tr>
</thead>
<tbody>
<tr>
<td>2009 - 2010</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>2010 - 2011</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>2011 - 2012</td>
</tr>
</tbody>
</table>
The suspicion that the Aveiro Port updrift beach has a very undetermined and undefined coastline is confirmed. During the 7 years studied, the advancement and retreat of coastline varied greatly and it goes from a retreat of almost 130 m at CD level between 2009 and 2010 to an advancement of more than 70 m in the period 2012 – 2013 also at CD level.

At the High Tide water level the modifications are less significant. The most extreme variance was of + 43.51 m between 2014 and 2015 the minimum was of – 12.57 in the period 2009 - 2010.

Summing up this analysis, the coastline retreated almost 60 m at the CD level in a beach profile 1 km north of the northern breakwater of Aveiro Port. It proves that the updrift influence of Aveiro Port breakwater, at the CD level, does not go that far since the beach retreated just 1 km far from this breakwater.

At the high tide level the coastline advanced 60 m between November 2009 and November 2016. This means that the multiple storms, wind and tides influence pulled the hydraulic dune into the shore and, with 7 years of sand movement, made possible the accretion of São Jacinto beach.

To complete this analysis, Profile 2 was also analysed and is represented in Figure 3.31.
Beach Profile 2 is only 190 m from the northern breakwater. There are also advancements and retreats, in very different scales, that occur since the first profile was developed 7 years ago. There’s a peak period at the CD level in 2013 and the peak period in the High Tide level occurred in 2015. The worst period of this beach profile, both at CD and High tide levels was in 2010, as shown in Table 3.12.

Table 3.15 was developed to identify accurately the advancement and retreat of São Jacinto coastline, 190 m from the northern breakwater.

<table>
<thead>
<tr>
<th>Year</th>
<th>CD</th>
<th>High Tide</th>
</tr>
</thead>
<tbody>
<tr>
<td>2009 - 2010</td>
<td>-122.87 m</td>
<td>-97.57 m</td>
</tr>
<tr>
<td>2010 - 2011</td>
<td>+77.05 m</td>
<td>+26.45 m</td>
</tr>
<tr>
<td>2011 - 2012</td>
<td>+9.46 m</td>
<td>+37.14 m</td>
</tr>
<tr>
<td>2012 - 2013</td>
<td>+112.47 m</td>
<td>+12.11 m</td>
</tr>
<tr>
<td>2013 - 2014</td>
<td>-187.92 m</td>
<td>-56.2 m</td>
</tr>
<tr>
<td>2014 - 2015</td>
<td>+105.98 m</td>
<td>+78.87 m</td>
</tr>
<tr>
<td>2015 - 2016</td>
<td>-25.27 m</td>
<td>-27.73 m</td>
</tr>
</tbody>
</table>

By analysing the retreat/advancement of the coastline in Profile 2 it is easy to understand how bigger the advancement rate in this Profile comparing to the Profile 1 is.

The most significant loss of coastline, at the CD level, was between 2013 and 2014, with a retreat of almost 190 m. In the opposite side, the greatest advancement in the surrounding area of the Aveiro Porto updrift breakwater, also at the CD level, was in the period 2012 - 2013 with an advancement of more than 110 m.

At the High Tide level the most significant changes were a retreatment of almost 100 m between November 2009 and November 2010 and an advancement of almost 80 m in the period 2014 - 2015.

In the 7 years studied period there were a general retreatment of the coastline both in High Tide and CD levels.

At the CD level the retreatment was of approximately 30 m and at the High Tide level, between 2009 and 2016, of more than 25 meters.

This analysis of beach profiles and advancement/retreat of the coastline prove how dynamic and hard to predict is the updrift area of Aveiro Port mouth and even though there were some years in which the advancement of the coastline was extremely significant, the overall analysis reveals that the updrift coastline of Aveiro Port is retreating.

The annual rate of advancement/retreat of the 12 beach profiles analysed in Aveiro Port surrounding area is in Table 3.16:

<table>
<thead>
<tr>
<th>TOTAL (m)</th>
<th>CD</th>
<th>HT</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1</td>
<td>-58</td>
<td>+59</td>
</tr>
<tr>
<td>P2</td>
<td>-31</td>
<td>-27</td>
</tr>
<tr>
<td>P3</td>
<td>-97</td>
<td>-7</td>
</tr>
<tr>
<td>P4</td>
<td>-243</td>
<td>-11</td>
</tr>
<tr>
<td>P5</td>
<td>-258</td>
<td>-6</td>
</tr>
<tr>
<td>P6</td>
<td>-87</td>
<td>+10</td>
</tr>
<tr>
<td>P7</td>
<td>+12</td>
<td>-30</td>
</tr>
<tr>
<td>P8</td>
<td>-134</td>
<td>-20</td>
</tr>
<tr>
<td>P9</td>
<td>-238</td>
<td>-6</td>
</tr>
<tr>
<td>P10</td>
<td>-161</td>
<td>-11</td>
</tr>
<tr>
<td>P11</td>
<td>-184</td>
<td>-42</td>
</tr>
<tr>
<td>P12</td>
<td>-112</td>
<td></td>
</tr>
</tbody>
</table>
In Figueira da Foz Port Authority required control data, there are 3 profiles to be studied updrift of Figueira da Foz. Since the more northern one is more than 2 km away from the updrift breakwater, the studied profiles will be just profile 2 and 3, represented in Figure 3.32 and Figure 3.33.

Profile 2, in Figure 3.32, represents the most northern profile which, along with Profile 3 represented in Figure 3.33, were used to calculate the accreted volume updrift of Figueira da Foz Port.

The advancement of the coastline is much more significant and constant in Figueira da Foz than in Aveiro. There’s a huge advancement in the 4 years gap when there were any profile register but then it continues to evolve since 2016.

The exact advancement/retreat of Figueira da Foz coastline in the last 6 years is in Table 3.17:

<table>
<thead>
<tr>
<th>Year</th>
<th>CD (m)</th>
<th>High Tide (m)</th>
<th>Total Advance (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010 - 2011</td>
<td>+20.62</td>
<td>+17.91</td>
<td>82.49</td>
</tr>
<tr>
<td>2011 - 2012</td>
<td>+20.62</td>
<td>+17.91</td>
<td>71.65</td>
</tr>
<tr>
<td>2012 - 2013</td>
<td>+20.62</td>
<td>+17.91</td>
<td></td>
</tr>
<tr>
<td>2013 - 2014</td>
<td>+20.62</td>
<td>+17.91</td>
<td></td>
</tr>
<tr>
<td>2014 - 2015</td>
<td>+ 9.22</td>
<td>+ 97.05</td>
<td></td>
</tr>
</tbody>
</table>
The table confirms that the advancement of coastline in Figueira da Foz northern beaches is enormous. The 4 years period can mislead in an analysis error, but dividing the values by 4, there’s an advancement of more or less 20 m every year both in CD and High Tide levels.

During the analyzed time, 6 years since 2010, there was an advancement of 95 m at the CD level. This perfectly proves the influence that Figueira da Foz Port northern breakwater has in the littoral sediments transport, its configuration that does not allow sand to go further south and how important it would be to artificially maintain the sand transport from north to south. From this data, with so many cubic meters of sand being trapped north of Figueira da Foz port every year, it is easy to understand how eroded is the southern part of Figueira da Foz River mouth (southern profiles represented in attachment).

Evolution of beach Profile 3 is represented in Figure 3.33 and helps to better understand the advancement of coastline in southern beaches of Figueira da Foz.

![Figure 3.33 - Beach profile evolution in Profile 3, Figueira da Foz](image)

This Profile, being only 60 m away from the northern breakwater, has a bigger accretion than Profile 2. It is notorious how bigger the beach gets every year and how it did not cease to increase year after year until 2016. From the analysis of this beach Profile evolution, there were, more or less, 200 m of coastline advancement in the last 6 year both at CD and High Tide levels. This proves not only how efficient is this sand trap but how stable could be the beaches downdrift if the longshore sediment transport was replaced. Here comes the need of a sand bypass system and how it could maintain sediment dynamics as natural as possible. It could avoid these constraints which are proven to influence not only the safety of populations by the sea but also recreational use of the whole city, Figueira da Foz.
The compilation of advancement/retreat of this beach Profile is represented in Table 3.18.

Table 3.18 - Retreat/advancement of the coastline in Profile 3, Figueira da Foz

<table>
<thead>
<tr>
<th>Period</th>
<th>CD Advance</th>
<th>High Tide Advance</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010 – 2011</td>
<td>+ 24.28 m</td>
<td>+ 16.14 m</td>
</tr>
<tr>
<td>2011 – 2012</td>
<td>+ 24.28 m</td>
<td>+ 16.14 m</td>
</tr>
<tr>
<td>2012 – 2013</td>
<td>+ 24.28 m</td>
<td>+ 16.14 m</td>
</tr>
<tr>
<td>2013 - 2014</td>
<td>+ 24.28 m</td>
<td>+ 16.14 m</td>
</tr>
<tr>
<td>2014 - 2015</td>
<td>+ 23.23 m</td>
<td>+ 27.43 m</td>
</tr>
<tr>
<td>2015 - 2016</td>
<td>+ 76.51 m</td>
<td>+ 39.73 m</td>
</tr>
</tbody>
</table>

+ 97.12 m at CD  + 64.55 m at High Tide

The accretion in the updrift beach of Figueira da Foz Port has no end. From 2010 to 2014 there was an accretion of almost 100 m at the CD level and 65 m at the High Tide level. This gives a medium increase of 20 m in this beach every year. One year after, in November 2015, the beach increase 25 m more and, when could be thought that the northern breakwater got saturated in sand trapping efficiency, the beach increase more than 75 m from November 2015 to November 2016.

Since 2010 until 2016 there were a little bit of everything in terms of wave regimes, breakwaters’ works, constant dredging of Figueira da Foz river mouth and navigational channel but one thing remains: there’s no retreat in the updrift beach of Figueira da Foz Port. The efficiency of northern breakwater as a sand trap is almost 100 %. The sand accumulates there year by year in a constant quantity of 500,000 m$^3$/year, but, unlike dozens of cases like this one all over the world, nothing is done to re-establish the natural sediment flow. Sand is dredged in the order of hundreds of thousands of cubic meters every year in to keep the navigation channel in proper conditions, but the sand is deposited in a place that will never mitigate the strongly felt erosion in the downdrift beaches of Figueira da Foz.

Table 3.19 contains the records of beach advancement/retreat for the 15 beach profiles along Figueira da Foz coastline. It is useful not only to understand how significant is the accretion updrift but also the erosion the downdrift beaches.

Table 3.19 - Annual advancement/retreat of Figueira da Foz Port adjacent areas

<table>
<thead>
<tr>
<th>Profile</th>
<th>P1</th>
<th>P2</th>
<th>P3</th>
<th>P4</th>
<th>P5</th>
<th>P6</th>
<th>P7</th>
<th>P8</th>
</tr>
</thead>
<tbody>
<tr>
<td>TOTAL (m)</td>
<td>CD</td>
<td>26</td>
<td>96</td>
<td>197</td>
<td>69</td>
<td>75</td>
<td>-28</td>
<td>-111</td>
</tr>
<tr>
<td></td>
<td>HT</td>
<td>-22</td>
<td>99</td>
<td>132</td>
<td>-1</td>
<td>22</td>
<td>-32</td>
<td>-39</td>
</tr>
<tr>
<td>Per Year (m)</td>
<td>CD</td>
<td>4.3</td>
<td>16</td>
<td>33</td>
<td>11.5</td>
<td>12.6</td>
<td>-4.6</td>
<td>-18.6</td>
</tr>
<tr>
<td></td>
<td>HT</td>
<td>-3.6</td>
<td>16.4</td>
<td>22</td>
<td>-0.1</td>
<td>3.6</td>
<td>-5.3</td>
<td>-6.5</td>
</tr>
<tr>
<td></td>
<td>P9</td>
<td>P10</td>
<td>P11</td>
<td>P12</td>
<td>P13</td>
<td>P14</td>
<td>P15</td>
<td></td>
</tr>
<tr>
<td>TOTAL (m)</td>
<td>CD</td>
<td>6</td>
<td>-22</td>
<td>-73</td>
<td>15</td>
<td>-24</td>
<td>27</td>
<td>-30</td>
</tr>
<tr>
<td></td>
<td>HT</td>
<td>-17</td>
<td>-21</td>
<td>-52</td>
<td>-24</td>
<td>-24</td>
<td>9</td>
<td>-8</td>
</tr>
<tr>
<td>Per Year (m)</td>
<td>CD</td>
<td>1</td>
<td>-3.7</td>
<td>-12.1</td>
<td>2.6</td>
<td>-4.0</td>
<td>4.5</td>
<td>-5</td>
</tr>
<tr>
<td></td>
<td>HT</td>
<td>-2.9</td>
<td>-3.4</td>
<td>-8.6</td>
<td>-4.0</td>
<td>-4.1</td>
<td>1.4</td>
<td>-1.4</td>
</tr>
</tbody>
</table>
4

BIBLIOGRAPHIC REVIEW AND INTERNATIONAL ANALOGOUS CASES OF SAND BYPASS

4.1. LITERATURE REVIEW

4.1.1. METHODOLOGY

In order to better understand sand bypass actions and efforts around the world in the last few years a resume had to be developed. The research started with a master thesis from the Faculty of Engineering of the University of Porto. Pedro Loza (2008) developed his master thesis in Environmental Engineering and did a very well resumed table about bypass systems around the world. At first sight there were sand bypass systems only in USA and Australia but that seemed sketchy.

P.K. Boswood and R.J. Murray (1997), by the time that viability studies for the Tweed River sand bypass system were being carried out, developed a very complete table resuming the majority of sand bypass systems implemented in the whole world.

The literature review table presented on the next pages started to be fully developed comparing this 1997s table with web research. Soon realized that a lot of information was outdated and was completely sank down in a whole world of bypass systems and trial systems in every single continent.

In the end, it all came from Italian systems with 80 years of age until the very last one, in Japan, constructed in 2014.

Direct contact was maintained with engineers responsible for almost every single one of those systems, hundreds of e-mails were exchanged to develop an extremely thorough table about bypass systems around the world.

The most shocking thing is, first of all, that fixed bypass systems are not a relatively recent invention. One of the most successful cases, the Nerang River’s, is operating since 1986 and marked an historic date in maritime engineering works. With a lot of improvements since then, causing a decrease in operation cost and an increasingly efficiency, it inspired 3 similar cases which are now implemented in 3 different continents in the world.

The first one is just 30 km away from Nerang River and was constructed in 2001. Tweed River sand bypass system is nowadays the most famous bypass system in the world. Hundreds of pictures are
taken every single day near bypass system infrastructures and it was responsible for maintaining the beautiful beaches of the Gold Coast in Australia safe and sound.

6 years passed since that and South African engineers of Transnet National Ports Authority, inspired by the successful of those two Australian cases and in consequence of the construction of a deep water port near Port Elizabeth, implemented the first fixed bypass system in a port. The main objective of this bypass system was to keep the normal littoral drift and to avoid the silting of the port navigation channel.

But as the Australian influence has no limits, in 2014 the most recent fixed bypass system in the world was implemented in Port of Fukude, Japan, as shown in Figure 4.1. It was constructed with the same purposed of the South Africa case.

![Fig. 4.1 – Most recent sand bypass system implemented, in Port of Fukude, Japan](image)

Anyway, what can be considered the most successful case is a Northern American one. In the state of Florida there are dozens of bypass systems, most of them using dredges and fixed pipeline systems buried in the ground, but one specific case can raise the biggest curiosity.

In South Lake Worth Inlet there is a fixed bypass system working, with a lot of improvements over the years, since 1937. In conclusion, then, the necessity to maintain the longshore sediment transport when a river entrance is established is known for a long time ago.

But the question that remains is how is it possible that after 80 years, after thousands of river entrances established in the whole world, to ensure the normal longshore sediment transport is not yet obligatory?

4.1.2. BIBLIOGRAPHIC DATABASE

The bibliographic database is listed in Table 4.1.
### Table 4.1 – Bibliographic database

<table>
<thead>
<tr>
<th>Location</th>
<th>Lifetime</th>
<th>Technical Solution</th>
<th>Wave regime (KW/m)</th>
<th>Bypassed volume (m³/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1  Adelaide (AUS)</td>
<td>2013-Now</td>
<td>Scrap a thin layer of built-up sand from the beach and pump via pipeline system to eroded beaches</td>
<td>◆ 2.5</td>
<td>150,000</td>
</tr>
<tr>
<td>2  Amanohashidate (JPN)</td>
<td>1985-Now</td>
<td>Dumping sand by truck in eroded beaches</td>
<td>◆ 0.2</td>
<td>5,700</td>
</tr>
<tr>
<td>3  Bandy Creek Harbour (AUS)</td>
<td>1989-Now</td>
<td>Dredge the entrance and nourish the downdrift beach</td>
<td>◆ 1.0</td>
<td>50,000</td>
</tr>
<tr>
<td>4  Barra do Furado (BRA)</td>
<td>Unfinished</td>
<td>Fixed structure with jet pumps updrift (jetty) and nourishment of downdrift beaches via pipeline</td>
<td>◆ 2.0</td>
<td></td>
</tr>
<tr>
<td>5  Boca Raton, FL (USA)</td>
<td>1980-Now</td>
<td>Dredge sand trap (weir jetty) to a pipeline system discharging downdrift</td>
<td>◆ 0.8</td>
<td>40,000</td>
</tr>
<tr>
<td>6  Bridgman, MI (USA)</td>
<td>1970-1973</td>
<td>Hydraulic bypass and sand from the dunes</td>
<td>◆ 0.0</td>
<td>75,000</td>
</tr>
<tr>
<td>7  Channel Islands Harbour, CA (USA)</td>
<td>1960-Now</td>
<td>Dredge sand trap (detached breakwater) to a pipeline system discharging downdrift</td>
<td>◆ 2.5</td>
<td>800,000</td>
</tr>
<tr>
<td>8  Dawesville (AUS)</td>
<td>1995-Now</td>
<td>Slurrytrak in the updrift beach to a pipeline system discharging downdrift</td>
<td>◆ 1.5</td>
<td>90,000</td>
</tr>
<tr>
<td>9  Durban (RSA)</td>
<td>1982-Now</td>
<td>Multiple systems since 1982 (fixed, mobile and semimobile)</td>
<td>◆ 2.0</td>
<td>600,000</td>
</tr>
<tr>
<td>10 East London Port (RSA)</td>
<td>1976-Now</td>
<td>Dredge sand trap (updrift breakwater) to downdrift beaches</td>
<td>◆ 2.0</td>
<td>600,000</td>
</tr>
<tr>
<td>11 East Pass, FL (USA)</td>
<td>1987-Now</td>
<td>Dredge the entrance and nourish the downdrift beach</td>
<td>◆ 0.5</td>
<td>40,000</td>
</tr>
<tr>
<td>Case Study</td>
<td>Time Period</td>
<td>Description</td>
<td>Cost</td>
<td></td>
</tr>
<tr>
<td>------------</td>
<td>-------------</td>
<td>-----------------------------------------------------------------------------</td>
<td>--------</td>
<td></td>
</tr>
<tr>
<td>Fire Island, NY (USA)</td>
<td>1954-1994</td>
<td>Dredge the entrance and nourish the downdrift beach</td>
<td>300,000</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1994-Now</td>
<td>-</td>
<td>400,000</td>
<td></td>
</tr>
<tr>
<td>Ft. Pierce, FL (USA)</td>
<td>1985-Now</td>
<td>Dredge sand trap (updrift breakwater) to downdrift beaches</td>
<td>30,000</td>
<td></td>
</tr>
<tr>
<td>Fukude (JPN)</td>
<td>2014-Now</td>
<td>Fixed structure with jet pumps updrift (jetty) and nourishment of downdrift beaches via pipeline</td>
<td>80,000</td>
<td></td>
</tr>
<tr>
<td>Hillsboro Inlet, FL (USA)</td>
<td>1997-Now</td>
<td>Dredge sand trap (weir jetty) to a pipeline system discharging downdrift</td>
<td>90,000</td>
<td></td>
</tr>
<tr>
<td>Hvide Sande (DEN)</td>
<td>1991-2011</td>
<td>Dredge the entrance to a pipeline system discharging downdrift</td>
<td>170,000</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2011-Now</td>
<td>-</td>
<td>140,000</td>
<td></td>
</tr>
<tr>
<td>Indian River Inlet, DE (USA)</td>
<td>1990-Now</td>
<td>Fixed structure with jet pump updrift (crane) and nourishment of downdrift beaches via pipeline</td>
<td>70,000</td>
<td></td>
</tr>
<tr>
<td>Jimmys Beach (AUS)</td>
<td>1983-Now</td>
<td>Dredge a sand build up area to a pipeline system discharging at eroded area</td>
<td>200,000</td>
<td></td>
</tr>
<tr>
<td>Jupiter Inlet, FL (USA)</td>
<td>1966-Now</td>
<td>Dredge sand trap (weir jetty) to a pipeline system discharging downdrift</td>
<td>60,000</td>
<td></td>
</tr>
<tr>
<td>Lake Worth Inlet, FL (USA)</td>
<td>1958-Now</td>
<td>Fixed structure with jet pump updrift (pump station with a crane) and nourishment of downdrift beaches via pipeline</td>
<td>150,000</td>
<td></td>
</tr>
<tr>
<td>Lakes Entrance (AUS)</td>
<td>2001-Now</td>
<td>Jet pump updrift and nourishment of downdrift beaches via pipeline</td>
<td>250,000</td>
<td></td>
</tr>
<tr>
<td>Lido Key, FL (USA)</td>
<td>1974-Now</td>
<td>Dredge adjacent river entrances to a pipeline system discharging at eroded area</td>
<td>100,000</td>
<td></td>
</tr>
<tr>
<td>Mandurah Inlet (AUS)</td>
<td>1995-Now</td>
<td>Slurrytrak in the updrift beach to a pipeline system discharging downdrift</td>
<td>100,000</td>
<td></td>
</tr>
<tr>
<td>#</td>
<td>Location</td>
<td>Period</td>
<td>Description</td>
<td>Cost</td>
</tr>
<tr>
<td>----</td>
<td>---------------------------------</td>
<td>-----------------</td>
<td>------------------------------------------------------------------------------</td>
<td>-------</td>
</tr>
<tr>
<td>24</td>
<td>Marina di Carrara (ITA)</td>
<td>1965-1985</td>
<td>Multiple systems between 1965 and 1985 (semi-mobile and fixed)</td>
<td>♦ 0.5</td>
</tr>
<tr>
<td>25</td>
<td>Masonboro Inlet, NC (USA)</td>
<td>1966-Now</td>
<td>Dredge sand trap (weir jetty) to a pipeline system discharging downdrift</td>
<td>♦ 2.0</td>
</tr>
<tr>
<td>26</td>
<td>Mexico Beach, FL (USA)</td>
<td>1973-Now</td>
<td>Slurrytrak in the updrift beach to a pipeline system discharging downdrift</td>
<td>♦ 1.0</td>
</tr>
<tr>
<td>27</td>
<td>Mooloolaba (AUS)</td>
<td>2012</td>
<td>Dredge the entrance to a pipeline system discharging downdrift</td>
<td>♦ 2.5</td>
</tr>
<tr>
<td>28</td>
<td>Murrells Inlet, SC (USA)</td>
<td>1980-Now</td>
<td>Dredge sand trap (weir jetty) to downdrift beaches</td>
<td>♦ 2.0</td>
</tr>
<tr>
<td>29</td>
<td>Navarre Beach, FL (USA)</td>
<td>2006 &amp; 2016</td>
<td>Dredge an offshore borrow area to the beach via pipeline system</td>
<td>♦ 1.0</td>
</tr>
<tr>
<td>30</td>
<td>Nerang River (AUS)</td>
<td>1986-Now</td>
<td>Fixed structure with jet pumps updrift (jetty) and nourishment of downdrift beaches via pipeline</td>
<td>♦ 1.3</td>
</tr>
<tr>
<td>31</td>
<td>Noosa Beach (AUS)</td>
<td>2012-Now</td>
<td>Sandshifter traps sand at the downdrift end of the beach and pumps it back to the eroded areas of the beach</td>
<td>♦ 2.5</td>
</tr>
<tr>
<td>32</td>
<td>Oceanside Harbour, CA (USA)</td>
<td>1987-Now</td>
<td>Multiple systems since 1987 (fixed and mobile)</td>
<td>♦ 2.0</td>
</tr>
<tr>
<td>33</td>
<td>Paradip (IND)</td>
<td>1963-Now</td>
<td>Dredge the entrance to a pipeline system (or rainbow technique) discharging downdrift</td>
<td>♦ 2.8</td>
</tr>
<tr>
<td>34</td>
<td>Perdido Pass, AL (USA)</td>
<td>1968-Now</td>
<td>Dredge sand trap (weir jetty) to downdrift beaches</td>
<td>♦ 0.5</td>
</tr>
<tr>
<td>35</td>
<td>Pinellas, FL (USA)</td>
<td>1966-Now</td>
<td>Dredge an offshore borrow area to the beach via pipeline system</td>
<td>♦ 0.9</td>
</tr>
<tr>
<td>Case Study</td>
<td>Year-Now</td>
<td>Description</td>
<td>Sand Volume (m$^3$)</td>
<td></td>
</tr>
<tr>
<td>------------</td>
<td>----------</td>
<td>-------------</td>
<td>--------------------</td>
<td></td>
</tr>
<tr>
<td>Point Roberts Marina, WA (USA)</td>
<td>2001-Now</td>
<td>Dredge sand trap (updrift breakwater) using bulldozers to downdrift beaches via trucks</td>
<td>8,000</td>
<td></td>
</tr>
<tr>
<td>Ponce de Leon Inlet, FL (USA)</td>
<td>1973-Now</td>
<td>Dredge the entrance to a pipeline system discharging downdrift</td>
<td>100,000</td>
<td></td>
</tr>
<tr>
<td>Port Canaveral, FL (USA)</td>
<td>1995-Now</td>
<td>Dredge updrift beach and pump via pipeline to downdrift</td>
<td>730,000</td>
<td></td>
</tr>
<tr>
<td>Port Everglades, FL (USA)</td>
<td>2019</td>
<td>Multiple options are studied and ready to be implemented</td>
<td>40,000</td>
<td></td>
</tr>
<tr>
<td>Port of Huelva (ESP)</td>
<td>1975-Now</td>
<td>Dredge the entrance and nourish the downdrift beach</td>
<td>1,000,000</td>
<td></td>
</tr>
<tr>
<td>Port of Ngqura (RSA)</td>
<td>2007-Now</td>
<td>Fixed structure with jet pumps updrift (jetty) and nourishment of downdrift beaches via pipeline</td>
<td>200,000</td>
<td></td>
</tr>
<tr>
<td>Port of Portland (AUS)</td>
<td>1996-Now</td>
<td>Sandshifter recovers sand from a trap 60 m offshore of the updrift breakwater and pumps it 3 km downdrift</td>
<td>50,000</td>
<td></td>
</tr>
<tr>
<td>Port Sanilac, MI (USA)</td>
<td>1970s-Now</td>
<td>Multiple systems since 1970s (mobile and semimobile)</td>
<td>10,000</td>
<td></td>
</tr>
<tr>
<td>Richards Bay (RSA)</td>
<td>1990s-Now</td>
<td>Dredge sand trap (updrift breakwater) to a pipeline system discharging downdrift</td>
<td>500,000</td>
<td></td>
</tr>
<tr>
<td>Rudee Inlet, VA (USA)</td>
<td>1949-Now</td>
<td>Dredge sand trap (updrift breakwater) to a pipeline system discharging downdrift</td>
<td>190,000</td>
<td></td>
</tr>
<tr>
<td>Santa Barbara, CA (USA)</td>
<td>1952-Now</td>
<td>Dredge the entrance to a pipeline system discharging downdrift</td>
<td>230,000</td>
<td></td>
</tr>
<tr>
<td>Santa Cruz, CA (USA)</td>
<td>1965-Now</td>
<td>Dredge the entrance to a pipeline system discharging downdrift</td>
<td>200,000</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Location</td>
<td>Year</td>
<td>Action Description</td>
<td>Port Everglades</td>
</tr>
<tr>
<td>---</td>
<td>----------------------------------</td>
<td>--------</td>
<td>------------------------------------------------------------------------------------</td>
<td>----------------</td>
</tr>
<tr>
<td>48</td>
<td>Sebastian Inlet, FL (USA)</td>
<td>2006-Now</td>
<td>Dredge sand trap (in the entrance) to a pipeline system discharging downdrift</td>
<td></td>
</tr>
<tr>
<td>49</td>
<td>Shinnecock Inlet, NY (USA)</td>
<td>1990-Now</td>
<td>Dredge the entrance and nourish the downdrift beach</td>
<td></td>
</tr>
<tr>
<td>50</td>
<td>South Lake Worth Inlet, FL (USA)</td>
<td>1937-Now</td>
<td>Fixed structure with jet pump updrift (pump station with a crane) and nourishment of downdrift beaches via pipeline</td>
<td></td>
</tr>
<tr>
<td>51</td>
<td>St. Lucie Inlet, FL (USA)</td>
<td>1974-Now</td>
<td>Dredge sand trap (weir jetty) to downdrift beaches</td>
<td></td>
</tr>
<tr>
<td>52</td>
<td>Tweed River (AUS)</td>
<td>2001-Now</td>
<td>Fixed structure with jet pumps updrift (jetty) and nourishment of downdrift beaches via pipeline</td>
<td></td>
</tr>
<tr>
<td>53</td>
<td>Ventura Harbour, CA (USA)</td>
<td>1970s-Now</td>
<td>Dredge sand trap (detached breakwater) to a pipeline system discharging downdrift</td>
<td></td>
</tr>
<tr>
<td>54</td>
<td>Viareggio Harbour (ITA)</td>
<td>1936-Now</td>
<td>Dredge multiple sources and pumping via submerged pipelines to downdrift jetty (hopper system to nourish when necessary)</td>
<td></td>
</tr>
<tr>
<td>55</td>
<td>Visakhapatnam (IND)</td>
<td>1975-Now</td>
<td>Dredge sand trap (detached breakwater) to rainbow technique/ floating pipeline discharging downdrift</td>
<td></td>
</tr>
</tbody>
</table>

The literature review resulted in a list of 55 bypass systems almost everywhere around the world, with the majority of them operating in the United States of America.

Below will be carried out a statistical review of this table and full analysis of each variable.

It is important to refer that:

- Port Everglades was not considered in “Bypass system” statistical analysis since the system to use was not decided yet;
- Barra do Furado was not considered in “Bypassed volume” statistical analysis since the system was never finished and system details are not specified;
- Barra do Furado and Port Everglades were not considered in “Start Year” statistical analysis because are not implemented yet.
Map from Figure 4.2 shows the colour-coding used to characterize wave regime in each place where a bypass system is operating. From here, one may conclude that even if United States of America has most of the bypass systems operating at the moment, excluding the Californian systems (west side of United States of America), the wave regime is nothing comparing to South African, Portugal or even Australia. This represents a great challenge, not only designing a fixed bypass system but also strictly characterizing the longshore sediment transport and possible volumes to be bypassed each year.

In Florida, the little peninsula in the South-eastern side of United States of America, even if the wave regime is not the strongest one, it is severely affected by storms and hurricanes. Not as frequent as South Africa and Europe are but East Coast of United States of America (Indian River Inlet) can also reach significant wave heights, like is shown in the graph presented in chapter 5.

4.1.3. STATISTICAL ANALYSIS

4.1.3.1. Bypass systems around the world

There is a big difference between United States of America and the other countries/continents regarding the number of sand bypass systems, as shown in Figure 4.3.
In Florida, especially, there are dozens of bays and corresponding connections between those bays and the ocean. Historical reports say that those inlets suffered from significant changes both in terms of location, flow, depth, etc. These changes started to worry the competent authorities and since the 1930s that those connections are studied and evaluated from the USACE and a lot of mathematical and physical modelling started to be done. Those inlets always represented multiple functionalities both for leisure or professional reasons and their depths had to be maintained. Dredging was always a solution to take into account but since the volumes to be dredge and the consistency of those operations would be relevant, bypass systems were considered. That is why there are so many sand bypass operations being carried out in the United States of American. From fixed to mobile through semimobile systems, all of them are implemented in the idyllic coast of Florida alone.

4.1.3.2. Starting year of the sand bypass operations

The biggest hype of the sand bypass systems was between the 70s and the 90s, as Figure 4.4 shows. Several factors can explain this situation:

- Development of pumps’ technology which made it possible to reduce bypassing operations costs;
- Establishment of several river entrances and the consequent need to maintain longshore sediment transport using sand bypass systems.

After the beginning of the new millennium, all the sand bypass systems implemented are semimobile or fixed. The need to maintain the longshore sediment transport is nowadays an almost mandatory subject.
The ports that were built after 2000 implemented a fixed sand bypass system since the beginning of its operations and dredging of navigation channel is nowadays unnecessary (Port of Ngqura in South Africa and Port of Fukude in Japan).

4.1.3.3. Type of sand bypass system

The sand bypass systems were classified according to the fixed, mobile or semimobile sand bypass systems definitions in chapter 1, and their distribution is in Figure 4.5.

Those systems containing a dredge or truck getting sand from an accreted area/sand trap and deposit it downdrift via a floating pipeline, rainbow technique or dumping were classified as mobile.

The ones which use a dredge connecting to a fixed pipeline system were called semimobile.

The fixed sand bypass systems are those with a jetty updrift, pump station, jet pump or submarine sand shifter in a very delimited area connected to a fixed pipeline system (across a bridge, bottom of the navigation channel, etc.).
4.1.3.4. Wave regime

Most of the sand bypass systems are implemented in locations where the wave energy is low. The implementation of the system in these locations is simplified:

- It is easier to quantify the longshore sediment transport since it is less changeable and consequently the annual bypass volume is lower;
- The capital investment is smaller since the structure (pipelines, pumps, jetty, etc.) does not have to be as robust as it would be in a strong wave regime.

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Fig. 4.5 – Number of sand bypass systems by type of system

Fig. 4.6 – Number of sand bypass systems for each range of wave energy
4.1.3.5. Tide range

The tidal height has as much influence in the design of a sand bypass system as the wave regime. That is the reason why there is only one sand bypass system in a location with a tidal height higher than 3 m, as seen in Figure 4.7.

These are some disadvantages with the increase of the tidal height:

- If the sand bypass system is mobile, the time window for dredging operations is lower and consequently the cost is higher;
- In a fixed system, if a jetty is required, the bigger is the tidal height, higher must be the structure, more robust and more expensive;
- Since the longshore sediment transport is highly affected by the tidal height, if the tidal height is higher, the longshore sediment transport is higher too, higher volume to bypass and higher costs.

![Tide range](image)

**Fig. 4.7 – Number of sand bypass systems for each tide range**

4.1.3.6. Annual bypassed volume

The bypassed volume is the most significant factor affecting the cost of bypassing operations. Even so, the number of bypass systems is well distributed between all the volume categories, as Figure 4.8 represents. Annual bypass volume is directly related to the longshore sediment transport and this last one does not only depend on the wave regime or tidal height.
4.2. INTERNATIONAL ANALOGOUS CASES OF SAND BYPASS

4.2.1. CHOOSING CRITERIA

After an exhaustive analysis, first to develop the bibliographic database, and then to choose, from those 55 locations around the world, 5 analogous cases to make a full and accurate description to complement the study about the two Portuguese cases, based on the following criteria:

- Type of structure – it must be a fixed bypassing structure, preferably;
- Operation years – it must be operating at the moment and implemented recently;
- Bypassed volume per year – it must have a bypassed average volume higher than 300,000 m$^3$/year, preferably;
- Wave regime – knowing that any bypass system in the world is operating in a place with wave action as heavy as Portugal, it must be as close as possible;
- Tide range – it must have a tidal range as close as possible to the Portuguese one: ~ 3.5 m.

Hereupon, even if not all the criteria were fulfilled, the 5 cases above were chosen:

- Indian River in United States of America;
- Nerang River in Australia;
- Port of Durban in South Africa;
- Port of Ngqura in South Africa;
- Tweed River in Australia.

4.2.2. CHARACTERISTICS OF THE SAND BYPASS SYSTEMS

Table 4.2 represents a summary with the characteristics of the 5 locations:
Table 4.2 – Characteristics of Case Studies

<table>
<thead>
<tr>
<th>Case</th>
<th>Type of Structure</th>
<th>Operation Years</th>
<th>Bypassed volume (m³/year)</th>
<th>Tide height (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Indian River</td>
<td>Fixed (crane updrift)</td>
<td>1990 - Present</td>
<td>80,000</td>
<td>1.5</td>
</tr>
<tr>
<td>Nerang River</td>
<td>Fixed (jetty updrift)</td>
<td>1986 - Present</td>
<td>500,000</td>
<td>1.3</td>
</tr>
<tr>
<td>Port of Durban</td>
<td>Semimobile (dredge to a pipeline system)</td>
<td>1982 - Present</td>
<td>500,000</td>
<td>2.0</td>
</tr>
<tr>
<td>Port of Ngqura</td>
<td>Fixed (jetty updrift)</td>
<td>2007 - Present</td>
<td>200,000</td>
<td>2.5</td>
</tr>
<tr>
<td>Tweed River</td>
<td>Fixed (jetty updrift)</td>
<td>2001 - Present</td>
<td>500,000</td>
<td>1.3</td>
</tr>
</tbody>
</table>

4.2.3. WAVE REGIME ANALYSIS

4.2.3.1. World wave energy resource map

Even if it is not the most rigorous way to determine how heavy is the wave regime in a certain location, the world energy resource map it is very useful to give us a first idea on how different is the wave energy in different locations around the world.

There is a notorious low energy wave regime around the equatorial line, a stronger regime in the southern part of the planet and then another 2 different peaks of high energy wave.

One of those peaks affects an area from Greenland and Iceland until Ireland. Western part of Europe gets the second strongest part of that high wave energy peak. The other wave energy peak has its strongest area in the Pacific Ocean and the most affected area is the Western part of the United States of America. The Southern part of the planet affected by the biggest high energy wave peak is South Africa and Southern part of Australia and New Zealand.

The 5 international analogous cases of sand bypass around the world are in the map of Figure 4.9.

Fig. 4.9 – World wave energy resource map (analogous cases locations)
This map represents very well how heavy the wave regime in Portugal is. Nerang and Tweed River being in the Eastern part of Australia are not affected by that southern high wave energy peak. Indian River, by analyzing this map, just gets the leftovers of the northern Atlantic Ocean peak of wave energy.

There 3 locations are nothing compared to the wave regime in Portugal. However, Port of Durban and Port of Ngqura, located in South Africa, have a similar wave regime with Portugal, being affected by the big peak of wave energy that hits the Southern part of South Africa.

4.2.3.2. Wave buoys reports

To better compare the wave regimes and understand better how close to the Portuguese wave regime the other studied locations are, wave data from local buoys in each one of those places, including Portugal, were collected and managed to create the graph of Figure 4.10 with the comparison of Significant Wave Height (Average height of highest 1/3 of all waves) and Maximum Wave height for a period of six years. Wave data from Durban and Ngqura were provided by CSIR (Council of Scientific and Industrial Research) and from Leixões Buoy by the hydrographic institute of Portugal. Both for Tweed/Nerang River (https://www.qld.gov.au/environment/coasts-waterways/beach/waves-sites/tweed-heads) and Indian River (http://www.ndbc.noaa.gov/station_page.php?station=41009) cases, wave data is available on the web.

Appendixes 1 and 5 contains the rest of the wave buoys analysis for these 5 locations between 2011 and 2016.
Fig. 4.10 – Hs comparison between the 5 international analogous cases
The chart was developed using 8 wave records per day: one at midnight and then every 3 hours. Some time periods, for some locations, are empty due to buoys operational problems from different sources. The nearest buoy to Port of Ngqura is only operating since 20th of April 2011 and then all the records for each location were only considered from that date since 31st of December 2016.

This meticulous and important comparison chart could only be developed due to the prompt support and help from the local entities responsible for the management of those wave buoys.

Nerang and Tweed River, located not more than 30 km from each other, were considered as just one location in order to simplify the interpretation of the chart.

The 5 different wave buoys reports were distributed in such a way that the weakest wave regime comes first and all the lines can be easily read.

### 4.2.3.3. Storm analysis

To better compare the different wave regimes in each one of these 5 locations there is the need to divide the records in civil years and point out the number of storms per year. The storms are divided into Minor (Min.) and Severe (Sev.) and the criterion used to classify them was, in accordance with the criteria used by Tweed River Entrance Sand Bypassing Project (TRESBP) as follows:

- **Minor storms:** $H_s \geq 3m$;
- **Severe storms:** $H_s \geq 5m$.

The compilation of number of Minor and Severe storms in sand bypass systems location, between 2011 and 2016, is in Table 4.3.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Aveiro/Figueira da Foz</td>
<td>48</td>
<td>6</td>
<td>61</td>
<td>8</td>
<td>92</td>
<td>19</td>
</tr>
<tr>
<td>Durban</td>
<td>22</td>
<td>1</td>
<td>15</td>
<td>0</td>
<td>10</td>
<td>0</td>
</tr>
<tr>
<td>Ngqura</td>
<td>10</td>
<td>0</td>
<td>13</td>
<td>0</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>Tweed/Nerang River</td>
<td>4</td>
<td>0</td>
<td>7</td>
<td>0</td>
<td>7</td>
<td>2</td>
</tr>
<tr>
<td>Indian River</td>
<td>8</td>
<td>1</td>
<td>5</td>
<td>4</td>
<td>12</td>
<td>2</td>
</tr>
</tbody>
</table>

**NOTES:**
- 2011 - Considering that the highest wave period in Europe is from December to March;
- 2016 - Considering that the most aggressive wave period of the year for Aveiro Figueira da Foz, January, was not recorded by the wave buoy.

By analysing Table 4.3, is clear how different is the wave regime when compared to the other studied locations. Durban an average of 17 minor storms per year and is the most similar to Aveiro/Figueira da Foz wave regime. Leixões (the one used regarding Aveiro and Figueira da Foz Ports areas) wave buoy
registered an average of 73 minor storms per year which is more than 4 times the number of minor storms per year in Durban. This analysis represents the clearest proof that any sand bypass system in the whole world is operating in a coastline as dynamic as the Portuguese one.

4.3. OVERALL ANALYSIS

4.3.1 INDIAN RIVER INLET, UNITED STATES OF AMERICA

4.3.1.1. Background

The coastline where Indian River Inlet is located, Delaware Atlantic coastline, is a sandy shore that spans approximately 40 km. The longshore sediment transport is in a medium range (around 150,000 m$^3$/year) and large storms often hit that part of the coast (Kirk F. Bosma et al., 1996).

After multiple failed attempts to keep the Indian River Inlet, represented in Figure 4.11, open by dredging alone, the 150 m wide inlet was constructed in 1939 by the US Army Corps of Engineers. When the constructions occurred the shoreline was relatively even on both sides but the navigable conditions were miserable. The two rubble mound breakwaters successfully establish a stable passage way from the inner bays to the Atlantic Ocean. This stabilization caused an increase of the bay salinity, reduced stagnation of the bays and increased the tide range (Thompson and Dalrymple, 1976).

![Indian River Inlet](image)

Fig. 4.11 – Indian River, United States of America

Apart from these consequences, the main problem was the erosion downdrift of the inlet. Route 1 highway travels parallel to the shoreline and in the following years of the inlet stabilization it was endangered.
Between 1957 and 1990, mitigation of the beach erosion was accomplished by dredging of the inlet and placement in the downdrift beach (northern side of the inlet, as shown in Figure 4.12).

Since 1990 a fixed sand bypass system operates in the updrift side of the inlet.

4.3.1.2. Plant data

This is a special kind of fixed bypass system. It’s usually called a fixed system because the crane doesn’t have as freedom in the borrow area as a dredge would have in the ocean.

The bypass system was designed to:

- Deliver approximately 130 m$^3$ of sand per hour of pumping to the downdrift beach;
- Bypass a target quantity goal of 75,000 m$^3$ of sand per pumping season (from September until May).

It is composed by:

- Crane supporting a jet pump located in the updrift beach;
- Pump House close to the updrift jetty;
- Pipeline system across the bridge located upstream of the river entrance;
- Discharge point in the downdrift beach.
4.3.1.3. Process Description

Clearwater intake is located in the inlet. A centrifugal supply pump (Gould 3410L 8” x 10” with a 21” diameter impellor) driven by an 8 cylinder diesel engine pumps water at a rate of 570 m$^3$/hour through a pipeline into the jet pump supported by the crane. Jet pump is used to remove sand from the accretion area and then a pipeline drives the slurry (mixture of sand and salt water) to the pump house. A booster pump (10” x 12” centrifugal pump with a 34” impellor manufactured by Pearce Pumps) powered by a 12 cylinder CAT diesel is located in the pump house and from there the slurry goes directly to one of the discharge point implemented downdrift.

The sand properties are as follows:

$D_{50} = 300$ to $400$ µm.

4.3.1.4. Operational Problems

The most significant problem associated with the bypass system is due to the very salty air environment. It affects mostly the crawler crane which had to be extensively rebuilt in 2014 at a cost of 640,000 €.

4.3.1.5. Costs

Table 4.4 contains the bypassed volume during each year of Indian River Sand Bypass System Operation.

<table>
<thead>
<tr>
<th>Year</th>
<th>Bypassed Volume (m$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1990</td>
<td>85,000</td>
</tr>
<tr>
<td>1991</td>
<td>60,000</td>
</tr>
<tr>
<td>1992</td>
<td>50,000</td>
</tr>
<tr>
<td>1993</td>
<td>50,000</td>
</tr>
<tr>
<td>1994</td>
<td>65,000</td>
</tr>
<tr>
<td>1995</td>
<td>55,000</td>
</tr>
<tr>
<td>1996</td>
<td>75,000</td>
</tr>
<tr>
<td>1997</td>
<td>85,000</td>
</tr>
<tr>
<td>1998</td>
<td>90,000</td>
</tr>
<tr>
<td>1999</td>
<td>70,000</td>
</tr>
<tr>
<td>2000</td>
<td>25,000</td>
</tr>
<tr>
<td>2001</td>
<td>25,000</td>
</tr>
<tr>
<td>2002</td>
<td>60,000</td>
</tr>
<tr>
<td>2003</td>
<td>85,000</td>
</tr>
<tr>
<td>2004</td>
<td>35,000</td>
</tr>
<tr>
<td>2005</td>
<td>35,000</td>
</tr>
<tr>
<td>2006</td>
<td>40,000</td>
</tr>
</tbody>
</table>
Operating costs are shared at the rate of 60% State of Delaware and 40% US Army Corps of Engineer. The operating costs for the period from March 1, 2016 to May 31, 2016 were 62,844 € (Dan Brower, 2017). This amount includes salaries (three people are required for permanent staff: one operates the crane while the other monitors the controls in a nearby building. A third person is necessary to operate a front-end loader), electricity, diesel fuel, supplies, and materials. If one make a simple calculation:

\[
Cost \text{ per year} = 62,844 \times 9 = 555,000 \text{ €}
\]

Dividing this value by the maximum bypassed recorded:

\[
Cost \text{ per cubic meter} = \frac{555,000}{100,000} = 5.55 \text{ €/m}^3
\]

If the worst year is considered, when the bypassed volume was only 25000 m\(^3\) the cost per cubic meter would be:

\[
Cost \text{ per cubic meter} = \frac{555,000}{25,000} = 22.6 \text{ €/m}^3
\]

Considering that the tendency between 2008 and 2012 (even only counted until mid-2012, the amount of sand bypassed is already larger that most of the previous years) was to bypass more and more sand each year, an average value of 5.55 €/m\(^3\) can be admitted.

The costs were originally in United States Dollars. The used exchange rate was:

\[
1 \text{ USD} = 0.853398874 \text{ €}
\]

4.3.2. Nerang River, Australia

4.3.2.1. Background

The Gold Coast seaway in Nerang River, Australia is the first fixed sand bypassing system implemented in the whole world. It is operating since 1980s and it is to last.
Nerang River inlet used to move northward or southward more than 60 meters each year and was incredibly dangerous because of the permanent south-easterly winds, significant northern drift of sand and severe wave climate. These factors combined resulted in 500,000 m$^3$ of sand moving along the coast each year (from the left to the right side of Figure 4.13).

In 1983 the government took action to stabilise the river mouth and intensive studies were conducted. The construction of two breakwaters south of the inlet was the most viable option but they could not create a physical barrier to the northward drift of sand. Hereupon, the two breakwaters orientated 15 degrees north of east and make the southern one a little bit larger to reduce the entry of ocean swells would have to be completed with a bypass system.

As no comparable system existed elsewhere at that time, the task of developing a fixed bypass system was a hard one.

With satisfactory answers to all questions, in the same year the government decided that Nerang River entrance stabilisation should proceed.

4.3.2.2. Plant data

The sand bypass system consists of:

- An offshore jetty south of the seaway southern breakwater housing 10 jet pumps (schematic view of a jet pump represented in Figure 4.14);
- The main pump station situated at the shore end of the jetty;
- A seawater pumping station;
- A slurry transfer pipeline approximately 1.4 km long.
The offshore jetty, approximately 500 m long, runs from the beachfront directly into the ocean. It provides the support structure for mounting jet pumps and associated supply and delivery pipelines to transfer beach sands to the onshore transfer pipeline.

The main pump station is located at the shore end of the jetty. It includes a sump and slurry pump to transfer sand slurry via the transfer pipe to the northern side of the seaway. Jet water supply pumps as well as associated electrical switch gear and system control equipment are also located in the main pump station.

The seawater supply pump station is located on the broadwater. Two vertical axial flow pumps in this pump station provide seawater to the jet water supply pump in the main pump station.

The slurry transfer pipeline is 400 NPS and transfers sand slurry from the main pump station under the seaway for discharge on the northern side of the northern breakwater. The pipeline is approximately 1.4 km long.

4.3.2.3. Process Description

The entire operation is explained in Figure 4.15. A jet pump operates by providing a high velocity upwards flowing jet of water which entrains sand. The supplied water must be free of sand due to the high velocity of the water in the jet. Two vertical axial flow pumps, in parallel (K L Berkeley M12 X 2 Stage Axial Flow Vertical Pumps manufactured by Wormald Machinery Pump Group, Sth Aus, with a 150 kW 3.3 kv caged induction motor), installed in the seawater pump station, supply sea water to the main pump station. Then, two centrifugal pumps (K L Worthington 10LN26B Horizontal split case double pressure volute pumps driven by a 560 kW 3.3 kv caged induction motor) supply high pressure water to the jet pumps located on the offshore jetty.

The jetty contains ten Genflo jet lift pumps to serve the 300 m length of the sand trap (any four or seven pumps can operate at any one time). During normal operation one low pressure sea water pump and one high pressure jet water supply pump are enough to supply four jet pumps and transfer the average sand volume. The second sea water supply, the jet water supply pumps and the other 3 jet pumps are only required when peak transfer rates are needed.

Each one of the ten jet pumps discharge into an elevated pipe flume transferring sand slurry to the transfer pump station. The elevated flume commences at the sixth jet pump from the shore and the other four jets furthest from the shore are connected to it by individual delivery lines.
The Genflo jet pumps are designed specifically for sand dredging operations and to be non-clogging under fully buried conditions, being the perfect solution for sand traps in bypass systems. Each pump includes integral fluidising jets which expand and fluidise the sand bed, enabling sand to be freely entrained by the jet pump at a controlled concentration. As sand is excavated from the region around the pump, the sand bed collapses to maintain a fluid bed adjacent to the pump. The trap continues to expand until empty when the walls stabilize at the prevailing angle of repose. When this occurs the jet pump is shutdown.

The elevated flume, 370 m long and a slope of 2.5 %, is built in 600 NB spiral welded steel pipe polyurethane lined for extend life. It is designed to provide a non-blocking transfer system whatever it is the range of flow rates or solid concentrations. Each jet pump discharges separately into the flume what makes its performance not affected by the discharge pressure of other pumps, enabling the jet pump units to be properly balanced for equal performance.

This elevated flume discharges into a conical sump with capacity for 145 m\(^3\). A variable speed slurry pump transfers sand slurry from this sump through the discharge line to the disposal area. The slurry transfer pump is a Warman 14/12 G-AH centrifugal slurry pump, driven via a gear box from a 4 pole 3.3 kV 710 kW electric motor. The transfer pump station sump receives sand from the jetty pipe flume as a 28-32 % concentration slurry.

During peak flow operation, the sand transfer pump will deliver slurry at a higher density than the flume delivers. Excess seawater will overflow the sump and gravitate through a pipe drain back to sea.

The transfer pipeline (under the Nerang River entrance) is built in three sections, all welded steel pipelines polyurethane lined (D = 400 mm). The pipeline is built up from pipe sections each 12.25 m long with specially developed coupling suitable for welding polyurethane lined pipes.

The first leg of the pipeline running from the main pump station to the seaway is approximately 230 m long. The second one is approximately 770 m long, crosses the Gold Coast Seaway and is protected by a reinforced coating of cement screed, 25 mm thick. The pipeline is supported on eleven steel piles under the seaway. The steel piles are 600 mm in diameter and 12 mm wall thickness. The third leg is 500 m long commencing at a branch line and heading east. The end section on the beach is supported on concrete piling with a branch line to either discharge into the surf zone or south along the beach.

The system is designed to transfer a maximum 490 L/s of slurry at 40 % solids against 70 m total dynamic head during peak flow operation.
The sand properties are as follows:

- $D_{90} = 450 \, \mu m$
- $D_{50} = 230 \, \mu m$
- $D_{10} = 170 \, \mu m$

4.3.2.4. Operational Problems

Major problems, since the first days of operation, were related with debris and consequently clogging of the jet pumps. This problem was soon solved by the maintenance engineers: a clean-out jet pump, with a diffuser opening of 9 inches, as opposed to the 3.5 inch opening on the normal jet pumps, has been constructed and was tested in late 1987 and early 1988. It was able to bypass a significant amount of large trash. Plans are to operate it periodically at each jet pump location, hopefully restoring performance of the regular jet pumps to design level. The one clean-out pump requires the entire output from the supply pump, making it impractical to install multiple debris clearing pumps. In addition, the shrouds on the existing jet pumps are being removed in an attempt to improve performance.

![Debris from the cleaning of a single jet pump](erdc-library.erdc.dren.mil)

4.3.2.5. Costs

Table 4.5 contains a full description of Bypassed volumes, hours of operation and total and unit costs per year and per cubic meter since the beginning of Sand Bypassing Operations.

<table>
<thead>
<tr>
<th>Period</th>
<th>Bypassed volume (m$^3$)</th>
<th>Hours</th>
<th>m$^3$/hour</th>
<th>€ Total</th>
<th>€/m$^3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1985-1986</td>
<td>90,000</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1986-1987</td>
<td>595,000</td>
<td>2,270</td>
<td>262</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1987-1988</td>
<td>470,000</td>
<td>2,039</td>
<td>230</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1988-1989</td>
<td>390,000</td>
<td>2,066</td>
<td>190</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Year</td>
<td>Volume</td>
<td>People</td>
<td>Water</td>
<td>Total Cost</td>
<td>Cost/Unit</td>
</tr>
<tr>
<td>------------</td>
<td>--------</td>
<td>--------</td>
<td>-------</td>
<td>------------</td>
<td>-----------</td>
</tr>
<tr>
<td>1989-1990</td>
<td>380,000</td>
<td>2,103</td>
<td>180</td>
<td>263,000</td>
<td>0.69</td>
</tr>
<tr>
<td>1990-1991</td>
<td>435,000</td>
<td>1,568</td>
<td>278</td>
<td>235,200</td>
<td>0.54</td>
</tr>
<tr>
<td>1991-1992</td>
<td>375,000</td>
<td>1,433</td>
<td>263</td>
<td>295,000</td>
<td>0.79</td>
</tr>
<tr>
<td>1992-1993</td>
<td>280,000</td>
<td>1,210</td>
<td>232</td>
<td>370,800</td>
<td>1.32</td>
</tr>
<tr>
<td>1993-1994</td>
<td>569,000</td>
<td>1,642</td>
<td>347</td>
<td>380,000</td>
<td>0.66</td>
</tr>
<tr>
<td>1994-1995</td>
<td>579,000</td>
<td>1,518</td>
<td>382</td>
<td>453,000</td>
<td>0.79</td>
</tr>
<tr>
<td>1995-1996</td>
<td>420,000</td>
<td>1,117</td>
<td>376</td>
<td>443,150</td>
<td>1.06</td>
</tr>
<tr>
<td>1996-1997</td>
<td>586,000</td>
<td>1,539</td>
<td>381</td>
<td>485,300</td>
<td>0.83</td>
</tr>
<tr>
<td>1997-1998</td>
<td>584,000</td>
<td>1,686</td>
<td>346</td>
<td>540,000</td>
<td>0.92</td>
</tr>
<tr>
<td>1998-1999</td>
<td>624,000</td>
<td>1,674</td>
<td>373</td>
<td>504,000</td>
<td>0.81</td>
</tr>
<tr>
<td>1999-2000</td>
<td>629,000</td>
<td>1,927</td>
<td>326</td>
<td>414,700</td>
<td>0.66</td>
</tr>
<tr>
<td>2000-2001</td>
<td>760,000</td>
<td>2,164</td>
<td>351</td>
<td>414,000</td>
<td>0.55</td>
</tr>
<tr>
<td>2001-2002</td>
<td>594,000</td>
<td>1,601</td>
<td>371</td>
<td>432,400</td>
<td>0.73</td>
</tr>
<tr>
<td>2002-2003</td>
<td>730,000</td>
<td>1,712</td>
<td>426</td>
<td>459,300</td>
<td>0.63</td>
</tr>
<tr>
<td>2003-2004</td>
<td>605,000</td>
<td>2,145</td>
<td>282</td>
<td>502,000</td>
<td>0.83</td>
</tr>
<tr>
<td>2004-2005</td>
<td>663,000</td>
<td>1,933</td>
<td>343</td>
<td>490,000</td>
<td>0.74</td>
</tr>
<tr>
<td>2005-2006</td>
<td>697,000</td>
<td>1,798</td>
<td>388</td>
<td>385,700</td>
<td>0.55</td>
</tr>
<tr>
<td>2006-2007</td>
<td>688,000</td>
<td>1,767</td>
<td>389</td>
<td>479,700</td>
<td>0.70</td>
</tr>
<tr>
<td>2007-2008</td>
<td>770,000</td>
<td>1,964</td>
<td>392</td>
<td>406,800</td>
<td>0.53</td>
</tr>
<tr>
<td>2008-2009</td>
<td>627,000</td>
<td>1,558</td>
<td>402</td>
<td>674,400</td>
<td>1.08</td>
</tr>
<tr>
<td>2009-2010</td>
<td>553,000</td>
<td>1,477</td>
<td>374</td>
<td>580,500</td>
<td>1.05</td>
</tr>
<tr>
<td>2010-2011</td>
<td>732,000</td>
<td>1,750</td>
<td>418</td>
<td>612,300</td>
<td>0.84</td>
</tr>
<tr>
<td>2011-2012</td>
<td>608,000</td>
<td>1,619</td>
<td>376</td>
<td>516,400</td>
<td>0.85</td>
</tr>
<tr>
<td>2012-2013</td>
<td>580,000</td>
<td>1,591</td>
<td>365</td>
<td>552,700</td>
<td>0.95</td>
</tr>
<tr>
<td>2013-2014</td>
<td>537,000</td>
<td>1,641</td>
<td>327</td>
<td>691,600</td>
<td>1.29</td>
</tr>
<tr>
<td>2014-2015</td>
<td>588,000</td>
<td>2,102</td>
<td>280</td>
<td>574,000</td>
<td>0.98</td>
</tr>
<tr>
<td>2015-2016</td>
<td>627,000</td>
<td>2,178</td>
<td>288</td>
<td>612,000</td>
<td>1.00</td>
</tr>
<tr>
<td>2016-2017</td>
<td>332,000</td>
<td>1,147</td>
<td>289</td>
<td>504,000</td>
<td>0.66</td>
</tr>
</tbody>
</table>

Installation cost: approximately 34 M € (major costs were 21.5 M € for the training walls construction and dredging of the navigation channel and 4.3 M £ for the sand bypassing jetty and pumping system).

The average cost of each cubic meter bypassed is 0.84 €. This cost includes the following different costs:

- Electricity (average of 150,000 €/year);
- Salaries of the staff (average of 136,000 €/year);
- Maintenance and repairs (average of 200,000 €/year).
The staff is composed by three permanent people maintaining and operating the system. The plant is mostly operated during off peak electrical power and one of the three operation staff is on call each evening to ensure the plant is successfully operating (off peak electricity is provided between the hours of 11:00 pm and 07:00 am Monday to Friday and from 11:00 pm Friday night until 7:00 am Monday morning.

4.3.3. PORT OF DURBAN, SOUTH AFRICA

4.3.3.1. Background

The idea of Durban as a port dates to 1824 when the first European settlers made a landing with the intention of setting up a trading post.

Durban bay, also known as Bay of Natal back in that time was one of the few natural harbours available in the east coast of South Africa.

According to extensive research from Natal Museum director, Vasco da Gama, the Portuguese explorer, was the first to sight the Bay on Christmas Day in 1497 during a search for a route to India. It is because of this first encounter with the Durban bay in Christmas day that the bay was first called “Natal” in honour of the nativity.

The first harbour master was only appointed in 1839 or 1849 so perhaps Durban as a port should be considered from this time. Once the entrance sandbar was conquered Durban went on to rapidly become Africa’s busiest general cargo port and home to one of the largest and busiest container terminals in the Southern Hemisphere.

The progressive erosion of the beaches of Durban can be traced back to 1850 when harbour entrance channel works interrupted the natural longshore sediment transport.
Various attempts, including the construction of groins, were made to control this, but none were successful until 1938 when, following recommendations by a Belgian engineer G. Nijhoff, a scheme incorporating a series of long, low groins to prevent further erosion in conjunction with sand bypassing (with sand dredged from Cave Rock bight and pumped to the beach) for beach restoration was implemented (History and Heritage of Coastal Engineering, 1996).

During the early 1980s the old groins were demolished and new low level, permeable groins were constructed. A sand trap was created in the southern breakwater and a trailing suction hopper dredger started to remove the sand and pump into a sand trap just north of the north breakwater. Bypassing and beach nourishment were achieved by pumping the sand from the hopper along the beaches downdrift.

The accumulated volumes in the sand trap and consequently bypassed were registered between 1986 and 1992 and are represented in Table 4.6.

Table 4.6 – Bypassed volume per year, Port of Durban

<table>
<thead>
<tr>
<th>Period</th>
<th>Bypassed volume (m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1986</td>
<td>420,000</td>
</tr>
<tr>
<td>1987</td>
<td>450,000</td>
</tr>
<tr>
<td>1988</td>
<td>360,000</td>
</tr>
<tr>
<td>1989</td>
<td>470,000</td>
</tr>
<tr>
<td>1990</td>
<td>590,000</td>
</tr>
<tr>
<td>1991</td>
<td>620,000</td>
</tr>
<tr>
<td>1992</td>
<td>560,000</td>
</tr>
</tbody>
</table>

In 1993 a consulting port and coastal engineering company completed a detailed feasibility study for the Port Authority in which a fixed sand pumping installation updrift of the harbour to replace dredging was investigated. It was found that with the use of jet pumps buried permanently in the seabed (like the ones used in Nerang River, the only fixed structure operating at that time), coastal sediment movement could be trapped and discharged to the downdrift beach more effectively and at considerably lower life cycle cost than using the present sea going dredging equipment.

The detailed design of the system commenced in 2005 and involved the review of alternative bypassing systems, review of updrift accretion threatening the entrance channel, collection of wave data, and the mathematical modelling of sediment transport processes.

Although work was significantly advanced on the fixed embedded jet pump system, due to capital expenditure constraints, options were reassessed and a dredger reclamation berth and pumping to a hopper option was selected to minimise initial capital expenditure.

As part of the Entrance Widening Project of Port of Durban, the existing dredger reclaim facility and municipal sand hopper station infrastructure situated on the north bank of the existing channel (operating since 1982) had to be demolished.

The construction of a temporary sand supply system was carried out to last approximately 3 years and designed for a wave condition return period of 1:5 years.
The Harbour Entrance Widening and Deepening operation was completed in 2010 and by that time the feasibility and detail design of a new sand hopper system was already ongoing.

4.3.3.2. Plant Data

Transnet National Ports Authority (TNPA) is responsible for managing the littoral drift along the Durban coastline. TNPA decided to replace the demolished infrastructure (the temporary one) with a new dredger reclaim facility and sand pumping hopper stations.

The new system is what is called a semimobile bypassing system and consists of (PRDW, 2010):

- Sand trap incorporated in the southern breakwater;
- New TNPA dredger provided with an over-the-side connection and able to utilize the existing land-based reclaim equipment which was installed in the hopper structure;
- Clear water intake structure;
- Dredger reclaim connection and supporting structure;
- Sand hopper structure;
- Excess water facility to remove the majority of fines and returning excess seawater from the dredger discharge back to sea;
- Main pump station at the hopper facility booster pump;
- Interconnecting pipelines;
- Associated services (power supply, access roads, water, sewerage, communications, etc.

4.3.3.3. Process Description

The new dredger was purposely constructed for the use of TNPA. This trailing suction hopper-dredger takes the sand from the sandtrap on the southern side of the southern breakwater and, using an over-the-side connection, is able to utilize the existing land-based reclaim equipment which is installed near the hopper in the A-Berth. This permanent reclaim connection will take into account the difference in levels between the loaded and unloaded conditions of the dredge and the new reclaim berth. The pumping operation from the dredge to the hopper will be at least 40 minutes at a volumetric concentration of no lower than 20% (PRDW, 2010).

Clean water intake is required for the abstraction of make-up and fluidisation for the sand bypass facility. It will be located at the seaward end of the existing shortened tug jetty. This intake will incorporate a coarse screen, to prevent the entrainment of large debris into the clean water pumping system, and a submersible solids handling pump (and associated valves and pipeworks) (PRDW, 2010).

The renovated sand hopper structure is used for temporary storage of sand received from the dredger. Besides the sand storage area, it will incorporate a static bar inlet screen for screening of the slurry received from the dredger, an excess water extraction facility for the removal of excess seawater from the sand hopper and a possible screening/filtering to retain suspended solids prior to its discharge to the harbour basin, minimising the discoloration of the harbour basin water (PRDW, 2010).

This sand hopper is sized to accommodate up to 3 dredger hopper loads per day, with a storage capacity of the same order as the capacity of the old hopper (5,500 m$^3$). The maximum volume of sand delivered per dredger load will be 1,600 m$^3$ of solids occupying a bulk volume of 2,775 m$^3$ discharged at an average volumetric concentration of 20% (PRDW, 2010).
There is a gantry in the sand hopper and the function of this gantry is to support the pumps and pipework required to fluidise/re-suspend the sand stored in the sand hopper and feed the sand/seawater slurry to pump in the main pump station. It incorporates six submersible pumps and one fluidising pump along the length of the gantry structure. Each pump will be provided with vertical slides to allow for lifting and lowering during sand entrainment and maintenance activities (PRDW, 2010).

Pipelines are routed to avoid future development zones, following servitudes to be defined and agreed, while attempting to minimize the discharge length and pumping effort required (pipelines should be buried) (PRDW, 2010).

A PLC system monitors operating parameters like: motor temperature; slurry flow rate and density, pressure in the water lines upstream and downstream of pumps, etc. When pre-set limits of the latter parameters are exceeded during operation the PLC will shut-down the system according to the normal shut-down procedure (PRDW, 2010).

Constant operating and maintenance considerations are carried out in order to remove the debris that accumulate on the reclaim hopper coarse screen as well as finer debris that passes (PRDW, 2010).

All structures were designed for maximum durability in the marine environment with minimum requirements for major in-service maintenance and a Design life of 25 years (PRDW, 2010).

The hopper sand bypass system is currently being commissioned and a direct discharge line which bypasses the sand bypassing system is delivering sand directly to the beaches. The pipelines in use are HDPE, 58 mm outer wall and 900 mm internal diameter and have approximately 1,000 m long (TNPA, 2017), as is represented in Figure 4.18.

The system is designed to bypass a minimum of 500,000 m$^3$/year and in the last year 600,000 m$^3$ were bypassed.

The sand properties are as follows:

- Finest ($D_{50} = 201 \mu m$);
- Average ($D_{50} = 278 \mu m$);
- Coarsest ($D_{50} = 805 \mu m$).

4.3.3.4. Costs

According to Clive Greyling, a Civil Technologist of TNPA, the operational cost of the sand bypass system is 3.6 €/m$^3$. This cost includes the salary of a permanent operational team, electricity and maintenance.
4.3.4. PORT OF NGQURA, SOUTH AFRICA

4.3.4.1. Background

The Port of Ngqura is unique for two reasons. First, it is the only port in South Africa with environmental authorization for its construction and operation. The existing paleo-channel allows the convenience of a deep water port without needing to dredge large amounts of consolidated material.

Paleo-channels are riverbeds created when sea levels were lower and that now lie buried beneath the seafloor, filled with aggregate. The Ngqura paleo-channel enabled a deepwater port without the necessity to dredge large quantities of consolidated material, resulting in lower capital dredging costs.

Secondly, the Port of Ngqura is the first in the world to have a fixed sand bypass system, which is shown diagrammatically in Figure 4.19. This recreates the natural longshore sediment transport pumping the sand from the west to the east.

4.3.4.2. Plant data

It was a requirement, when the port was established, that the longshore sediment transport should be maintained from updrift to downdrift to avoid the harbour impact in that stretch of coastline.

According to Wayne Jansen from TNPA, which was the responsible for Port of Ngqura Sand Bypass System until June 2017, the bypass system was designed to:

1. Have sufficient capacity to bypass up to 320,000 m$^3$/year;
2. Have sufficient capacity to bypass a storm transport of 16,000 m$^3$ in five days;
3. Have a trap that extends across sufficient cross-shore profile to trap most of the longitudinal longshore transport;
4. Minimise the risk of material accreting in the entrance channel due to the accretion of the updrift beach and/or material passing the seaward end of the trap.

The system consists of:

- An offshore jetty located at the updrift beach (shown diagrammatically in Figure 4.20);
- A clear water intake;
- A main pump station situated at the shore end of the jetty;
• Booster pump stations;
• Pipelines’ system 3,800 m long.

The offshore jetty is 225 m long, located 150 m from the western breakwater, as shown in Figure 4.21, and is constructed within a pre-excavated sand trap, as shown in Figure 4.22, which provides short-term storage of sand capture when it is transported along the coastline. The jetty itself supports the jet pumps, pipework and valves, and provides access (pedestrian and vehicular) to this equipment for maintenance purposes. The vertical jetty pile at each jet pump position incorporates a system of guides to assist with the installation and removal of the jet pump and its vertical pipe string as well as to support the jet pump and pipe string in its final position once it is installed. The jet pump is completely shrouded to protect the jet pump from debris impact as well as to prevent the jet pump pipework from becoming entangled with debris.

The clear water intake is located within the third caisson of the western breakwater, which pumps seawater to the main pump station situated on the jetty. This location ensures that relatively sediment-free water can be extracted and, further, this location ensures that pipelines, power supply, etc do not cross any back of quay areas and will not restrict any future development in the outer basin reclamation area. The clear water intake components are housed in a cell that was specifically modified to accommodate two submersible pumps, pipework, coarse screens, a transformer and switchgear and access platforms and ladders.

![Fig. 4.19 – Jetty scheme (Transnet, 2017)](image)

The main pump station is to act as the control centre for the system and to house the electrical switchgear and transformers, motive pump, fluidiser and flushing water pumps, booster pump, mass flow meter, control room, office, workshop and ablutions.

The function of satellite booster pump stations located along the slurry discharge pipeline is to house the booster pumps required to supply the pressure head necessary to discharge the slurry to the downdrift breakwater discharge location. The booster pump stations also house transformers and switchgear required to supply power to the booster pumps. A gantry crane spanning each pump room has been provided for installation and maintenance of pump, pipe and valve components. The gantry travel covers a maintenance vehicle loading bay within the pump room.

Pipelines are to convey fluid. The fluid may be one of the following:

• Seawater containing some debris and a small quantity of sediment;
• Clear seawater;
• Sand/seawater slurry.
4.3.4.3. Process Description

Seawater is pumped from the clear water intake to the main pump station at the root of the jetty by low pressure solids handling submersible pumps. After fine screening of the seawater in the rotation drum screen, suspended sediment is settled out in the settling tank. The resultant clear seawater is then pumped to the jetty by a high pressure centrifugal motive pump where this high pressure flow is used to drive the jet pumps.

The low pressure fluidising/flushing water supply to the jet pumps is provided by a separate pump. The fluidising flow passes through a series of fluidising nozzles at the jet pump suction duct (intake), which creates a sand/water slurry fluid around the jet pump. Within the intake shroud of the jet pump, the high pressure motive flow passes through jet pump nozzle and the surrounding fluid is entrained by this jet, which together with the motive flow, discharges into a mixing chamber and onwards to the discharge line. In this way the pump can operate even if completely covered by sand.

When the sand bypass system is idle, low pressure flushing water flows through the motive nozzle and fluidising nozzles of each jet pump to prevent the ingress of sand into these nozzles.

The sand/water slurry discharged by the operational jet pump is pumped to the booster slurry pump (Warman centrifugal pump) located in the main pump station. A series of three further booster pumps positioned in satellite booster pump stations located within the port are provide the head required to pump the sand/water slurry to the downdrift breakwater discharge location.

In order to take advantage of the jet pump hybrid system and to ensure that energy employed in the system is conserved where possible, the slurry discharge line operates as an integrated system between the jet pumps and the boosters with no discontinuity in the sand/water flow.
Some improvements were done regarding these long discontinued flows with the implementation of heavy-duty cartridge mechanical seals with support systems in 2009. This solution has worked trouble free ever since, saving over 150,000 € in maintenance and repair costs, and has helps the station achieve a transfer rate 65% over the minimum requirement. These issues with the pumps happened due to the highly abrasive mix of sand and seawater that is pumped (22,000 tons per month).

![Diagram of Sandtrap transversal profile](Transnet, 2017)

The jetty system pumping rate will range between 110 and 520 tons/hour of in-situ material. The pumping rate will depend on the grading of material being pumped, the motive water pressure and the position of the jet pump being operated. This range of pumping rates is adequate to bypass the upper limit annual bypass volume of 320,000 m$^3$/year and by making use of short term storage in the sand trap is sufficient to cope with peak sand transport rates during storm conditions. The system, operated at the typical pumping rate of 200 m$^3$/hour for eighty percent of the available time, has the capacity to bypass in excess of seven times the average annual longshore sediment transport.

Jet pumps operate one at a time in a pre-determined programmed sequence and are automatically operated using a programmable logic controller (PLC). Typically, the jet pump with the greatest depth of sand over the pump inlet will be selected to operate first. Further pumps will then be selected for the pumping sequence in order of descending overlying sand thickness. The sand slurry created by the jet pumps contains 12-15% sand.

Four Warman 12/10 G-GH grave pumps incorporate the sand bypass scheme. Each pump is driven by a 550 kW direct coupled electric motor and will be capable of operating at 366 L/s at a maximum head of 83 m. Pump speed will be between 400 rpm and 700 rpm. The pumps have a three-vane closed impeller, specially designed to pump sand and gravel. The maximum particle size is 210 mm. The materials of construction in the pumps are abrasion resistant iron alloy. The pumps have a removable cartridge type bearing assembly with heavy duty shaft and taper roller bearing for the drive and nondrive end of the pump. Single bolt adjustment allows for quick regulation of the impeller to maintain pump efficiencies.

The pipeline running between the Warman pumps is buried is 400 mm OD HDPE while the piping that runs along the jetty is exposed and is steel with a polyurethane lining to combat erosion and corrosion, while considering thermal expansion constraints.
Sand is passed through four booster pumps (Alstom) to the discharge point situated on the downdrift breakwater (300 m out to sea). The discharge line is a pipeline 3800 m long.

The sand properties are as follows:

The sediment at three of the four studied stations was dominated by sand (> 98 % contribution), with the remaining station also mainly sand but with a higher gravel volume (13.39 %). Two of the four stations were dominated by medium-grained sand and at the other two stations fine-grained sand was the dominant class. From a textural perspective, three of the stations’ sediment were classified as sand and the remaining station was classified as gravelly sand (Theron, 2014). From this it can be concluded that the main sediment component at the Port of Ngqura is fine to medium-grained sand (Schmidt, 2016).

4.3.4.4. Operational Problems

The jet pumps of the sand-bypassing system can handle particles up to 150 mm, which means that all the coarse material with a diameter larger than 150 mm will cause an obstruction at the intakes. This problem has been solved with periodic dredging around the jet pumps to airlift the bigger rocks out.

So it is a more complex situation that it seems to be, lots of studies were carried out and some solutions to prevent the obstruction of the jet pump intakes appeared (Schmidt, 2016):

- Submerged groin: updrift of the jetty to work as a barrier for the larger particles;
- Piles and mesh structure: in the groin’s case the obstruction is caused by the low permeability of it, but if a higher permeability can be achieved, would be a better concept;
- Mobile jet pump: this solution aims to deal with the coarse material just after it is already located in the sand trap;
- Coarse material catchnet: similar to the pile and mesh structure but this one would be able to remove the coarse material from the coastal system involving constant clearance.

All the system is maintained by a permanent team working (system operator and his staff) that is responsible to monitor the whole system. They conduct daily soundings of the trap beneath the jetty to assess the state of the sand trap. These daily monitoring results are used by the system operator to assess where the sand has been deposited in the trap and therefore enable him to determine the day’s sand bypassing requirements and to set up the required jet pump operating sequence.

The Port of Ngqura follows a maintenance schedule lasting one week and performed every three months, which includes:

- The removal and installation of pumps with a crane for inspection and removal of marine growth;
- High pressure cleaning of pipe lines;
- Divers removing intake screens and marine growth in the caisson, and re-installing the intake screen;
- Daily removal of coarse material from the beach (sizes exceeding jet pump intake size).

This entire process takes approximately one week to complete, which means the bypassing process is halted for this period.
Table 4.7– Bypassed volumes per year (Schmidt, 2016)

<table>
<thead>
<tr>
<th>Year</th>
<th>2007</th>
<th>2008</th>
<th>2009</th>
<th>2010</th>
<th>2011</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bypassed volume (m$^3$)</td>
<td>18,800</td>
<td>77,400</td>
<td>50,700</td>
<td>59,000</td>
<td>41,000</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Year</th>
<th>2012</th>
<th>2013</th>
<th>2014</th>
<th>2015</th>
<th>2016</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bypassed volume (m$^3$)</td>
<td>86,500</td>
<td>130,000</td>
<td>143,000</td>
<td>182,000</td>
<td>41,400*</td>
<td>830,000</td>
</tr>
</tbody>
</table>

* - this volume is just until June 2016.

The target volume of 320,000 m$^3$/year were never achieved which is justified by Transnet as follows:

- Lack of replenishment of the sand in the sandtrap;
- The sandtrap is filled with debris;
- Only three of the six jet pumps are operational;
- All functional jet pumps were elevated from - 7.5 m to CD to - 4.1 m to CD;

The system is often now operating due to breakdown.

4.3.4.5. Costs

The implementation of the bypass system involved multiple tasks and different constructions such as:

- Preliminary study: 1,500,000 €;
- Maritime works (Intake structure, Sand Trap and Jetty): 1,900,000 €;
- Pump system (Pump Station, Pipelines, Earthworks, etc.): 2,800,000 €.

4.3.5. Tweed River, Australia

4.3.5.1. Background

Since the early days of Tweed River Inlet that sand bypassing started to be an option. River training works and dredging started to operate in the late 1800s in order to improve the safe navigation of Tweed River but because they were not enough, another measures started to be considered. This culminated in the extension of the training walls between 1962 and 1965.

The navigation conditions improved a little but some years passed and dredging works were required again. Accretion updrift and erosion downdrift also started to be noted and studies for the bypass structure were carried out with two objectives:

- Maintain a safe navigable entrance;
- Restore and maintain the amenity of the beaches on the southern Gold Coast of Queensland.

The construction was conducted in two stages:

1. Create a navigable channel by dredging more than 3,000,000 m$^3$ of sand from the channel to the southern beaches (downdrift) which was carried out during the construction of the bypass system;
2. Construct and operate of a permanent sand bypass system (as shown in Figure 4.23).

![Fig. 4.22 – Overview of Tweed River Sand Bypass System (tweedsandbypass.nsw.gov.au)](image)

The project was designed and constructed by McConnell Dowell with finance provided by the ANZ banking group, operate and transfer’ contract with the state government partners (New South Wales and Queensland) in a form of Public-Private Partnership.

The involvement of the private sector in the project was driven by a number of factors:

- Uncertain technology;
- Innovative approach;
- Cross jurisdictional aspects which required independent operation.

The use of this Public-Private Partnership allowed for the sharing of risk between the private partner and the government parties (Ware, D., 2016).

4.3.5.2. Plant Data

The main objectives of Tweed River sand bypass system design were:

- Create the most cost effective in terms of construction and operation;
- Address the safety risks associated with construction and operation of the facility;
- Minimise any adverse environmental impact of the facility;
- Optimise the quality and performance of the facility.

The system is just like Nerang River and Port of Ngqura cases:

- Sand collection jetty located at the updrift beach (Letitia Spit), housing jet pumps, as is shown diagrammatically in Figure 4.24;
- Clear water intake;
- Main pump station situated at the shore end of the jetty;
• Control building working as a pump station;
• Pipelines’ system with more than 7 km long.

The sand collection jetty is 450 m long, located 250 m south of the southern breakwater, as shown in Figure 4.25, and provides a sand trap by the operation of a series of ten submerged jet pumps. The sand trap is maintained as a permanent depression under the sand collection jetty and natural wave driven currents feed sand into it. In the early stages of operation, the accumulated sand reserve on Letitia Spit is also used to supply the sand traps.

The clear water intake is located in the Tweed River, supported by a steel piled structure and protected by screens at the pump inlet preventing large items from being drawn into the pump.

The control building holds a controlled environment which houses all electrical and control equipment, control room, maintenance facilities and staff amenities. A secure compound around the control building is provided for the safe storage of supplies including spare jet pump and pipework, including the medium density polyethylene (MDPE) pipe to be used for the temporary outlets (Duranbah case speaking). A comprehensive computerised control system is provided to operate and control the entire system (except outlet selection which is manual).

The system maintains full records of all operations and environmental monitoring summaries are made every single month contemplating characteristics as detailed as:

• Volumes pumped to each outlet;
• Dredging records;
• Indicative longshore transport;
• Tweed River entrance conditions and traffic records;
• Wave conditions;

![Jet pump scheme](https://coastadapt.com.au)
- Tide records;
- Media articles relating to the bypass system.

An example of a monthly monitoring summary is in appendix.

4.3.5.3. Process Description

The system is operated with up to five jet pumps operating together at one time and the sand slurry is discharged into a flume and flows under gravity to a slurry pit located on shore.

The discharge of each jet pump is monitored for slurry density to enable the operating jet pumps to be switched when the sand supply at each jet pump is exhausted. The jet pumps are the measure with less impact in the jetty environment, allowing a reduced risk of damage. This also simplifies the functions of the sand collection jetty to:

- Provide access over the sand trap area;
- Support the required pipework;
- Ensure the safety of jetty users during operations.

Maintenance requirements are also reduced, as all large plants items are located in protected environments. Platforms are provided at the jet pump locations for maintenance purposes.

The jet pumps are operated using high-pressure water drawn from the Tweed River upstream of the entrance.

Here, water free from sand, can be reliably obtained to reduce wear in the water pumping equipment. Clean salt water is collected at the low-pressure pump station (KSB-Ajax submersible pump incorporating a 146 Kw motor with a rating of 655 litres/second at 14.4 m) and is delivered to the control building via an underground 600 mm diameter medium density polyethylene pipeline to supply the high-pressure pump, which in turn supplies the jet pumps on the jetty.

A single high-pressure pump (Clyde Union manufactured Uniglide SDK 44/600B pump driven by a 1,100 kw motor which in turn is driven by a 3,300 volt variable speed drive which varies the pump speed to maintain a steady water pressure of 1,250 Kpa) supplies the high-pressure motive water for the jet pumps. The pump speed is adjustable and limits the maximum volume of sand delivered by the jet pumps to match the capacity of the sand transfer system. The control system automatically cycles combinations of the jet pumps to maintain the sand trap and optimise the sand delivery rate.

Sand slurry discharge from the jet pumps (internal design) is returned to shore via an inclined flume pipe to a slurry pit. A screening device is provided to prevent large items (shells, bricks, stones etc) picked up by the jet pumps from reaching and blocking the sand transfer system. These items are collected in a separate waste bin and disposed of appropriately.

The sand transfer system draws sand slurry from the pit and pumps it through a 400 mm diameter polyurethane lined steel slurry pipeline under the Tweed River to one of the two fixed or two temporary outlets that exist along the southern Gold Coast beaches or at Duranbah in New South Wales. The slurry pump in use is a KSB LCC GIW 10x12 – 125wr, coupled to a gearbox and 630 kw motor which is driven by a variable speed drive to maintain a slurry flow rate of 400 litres per second. This pump is capable of delivering slurry a distance of approximately 1.4 Km. If delivery sand further afield is necessary, a second pump/motor combination with a soft starter is installed, in series with the main pump.
The main fixed outlet is at Snapper Rocks East (1,210 m), and a secondary fixed outlet is located at Snapper Rocks West (2,018 m). A temporary outlet could not be assembled safely at Snapper Rocks West due to wave and tide action so a fixed outlet has been constructed by imbedding the pipeline in the rock platform. An outlet at Kirra (2,635 m) is assembled as necessary, and similarly at Duranbah (1260 m) the outlet can be located where it provides the best outcome for the area. The system is designed to discharge to only one outlet at a time - the operating outlet is selected by operating and locking valves, which are located at branches along the slurry pipelines.

Sand slurry is pumped from one of two slurry pumps, or two pumps in series depending on which outlet is selected. One variable frequency power supply is provided and normally connected to the first pump motor. The second pump is driven by a fixed speed drive. The variable speed drive will be used to vary the discharge pressure to control the pipeline operating velocity within safe limits and control the maximum slurry density in the pipeline to eliminate the possibility of blockages. The slurry pumps are configured using interchangeable spools to enable either pump to be operated alone for the closer outlets including the main operating outlet at Snapper Rocks East. The slurry pumps are configured to operate in series for the more distant outlets (Snapper Rocks West and Kirra Point).

The sand transfer system from the control building is designed to operate at slurry densities up to 50% by weight. The maximum slurry density would apply for sand transfers to the main outlet at Snapper Rocks East and also Snapper Rocks West. Lower slurry densities may be utilised when pumping to the remote temporary outlet at Kirra Point in order to reduce the maximum pumping head (Tweed Sand Bypassing, 2017).

The peak sand transport capacity is 625 m\(^3\)/hour (1,000 tonnes/hour) with an average bypassed volume of 500,000 m\(^3\)/year with operations being manly carried out at night.

The sand properties are as follows:

- \(D_{90} = 580 \mu m\);
- \(D_{50} = 270 \mu m\);
- \(D_{10} = 150 \mu m\).
4.3.5.4. Operational Problems

Operations issues include the blocking of the jet pumps both man-made and natural material (seaweed, tree branches, rags, etc) for which clearance multiple techniques were developed. These blockages happen frequently, mostly when the weather is stormy.

Recent studies have shown that the excess sand volumes are naturally dispersing from Coolangatta Bay and community concerns led to a campaign for changes to the system operation mode. Investigations were carried out in order to reduce the sand supply to the bay and to disperse the sand build up.

Four potential options were investigated:

- A new sand delivery outlet at North Kirra with an extension of the existing sand delivery pipeline by slightly over one kilometer;
- Additional Dredge Placement Areas potentially located along Bilinga and Tugun beaches about three kilometres to the north of the project placement areas, and also in deeper waters further offshore of the existing Point Danger to Coolangatta nearshore sand placement areas;
- Delivery of sand dredged from the Tweed River entrance to Kingscliff for beach nourishment of the eroded south Kingscliff Beach;
- Sand Back-passing by either dredge placement and/or pumping of sand southwards along Letitia Spit Beach.

4.3.5.5. Cost

The bypass system is currently a big success with recognition all over the world. It bypassed more than 8 million m$^3$ of sand from Leticia Spit (NSW) into Queensland and it had a variable cost each year since the beginning of the project.

Since it was an involvement between private sector and two states, the cost has been amortized since the beginning of its operations. The division was made like:

- 75 % for New South Wales State Government and 25 % for Queensland State Government and Gold Coast City Council, during design and construction phases;
- 50 % for New South Wales State Government and 50 % for Queensland State Government and Gold Coast City Council, for the operational phase.

The establishment cost of the system were paid by an initial payment of about 1.3 M € and repayments of about 2.0 M €/year over the first 12 years of operation.

\[
Cost\ of\ construction = 1,300,000 + 12 \times 2,000,000 = 25,300,000 \text{ €}
\]

Apart from that, the rest of the annual cost is for operational costs which include:

- Electricity;
- Salaries of the staff (3 permanent people working on the system);
- Maintenance and repairs.

Table 4.8 contains the annual bypassed volume of sand and respective costs, without considering the amortization.
Table 4.8 – Bypassed volume and costs per year

<table>
<thead>
<tr>
<th>Year</th>
<th>Bypassed Sand (m$^3$)</th>
<th>€ Total</th>
<th>€/m$^3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2001</td>
<td>575.869</td>
<td>2,112,000</td>
<td>3.67</td>
</tr>
<tr>
<td>2002</td>
<td>721.364</td>
<td>4,224,000</td>
<td>5.85</td>
</tr>
<tr>
<td>2003</td>
<td>787.026</td>
<td>5,544,000</td>
<td>7.04</td>
</tr>
<tr>
<td>2004</td>
<td>496.367</td>
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<td>724.931</td>
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<td>552.284</td>
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<tr>
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<td>585.809</td>
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<tr>
<td>2009</td>
<td>409.232</td>
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</tr>
<tr>
<td>2010</td>
<td>395.609</td>
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<td>6.51</td>
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<td>518.169</td>
<td>2,508,000</td>
<td>4.84</td>
</tr>
<tr>
<td>2012</td>
<td>436.092</td>
<td>2,508,000</td>
<td>5.75</td>
</tr>
<tr>
<td>2013</td>
<td>319.883</td>
<td>2,640,000</td>
<td>8.25</td>
</tr>
<tr>
<td>2014</td>
<td>465.501</td>
<td>528,000</td>
<td>1.14</td>
</tr>
<tr>
<td>2015</td>
<td>552.682</td>
<td>1,188,000</td>
<td>2.15</td>
</tr>
</tbody>
</table>

The average cost per cubic meter is: 6.17 €/m$^3$.

The costs were originally in Australian Dollars. The used exchange rate was:

\[ 1 \text{ AUD} = 0.680551466 \text{ €} \]
5

SAND BYPASS AS A MITIGATION FOR BEACH EROSION DOWNDRIFT OF AVEIRO AND FIGUEIRA DA FOZ PORTS

5.1. SAND BYPASS SYSTEM AND ITS ADVANTAGES/DISADVANTAGES

5.1.1. APPLICATION OF SAND BYPASS SYSTEMS

One of the possible solutions to the erosion problem, commonly occurring downdrift of jettied river entrances caused by stoppage of passage of the normal drift by the jetty barrier, is periodic replenishment of material on the eroded beach. This material is frequently taken from the accreting area updrift from the jetties (Rudolph P. Savage, 1957).

This is a clarification of what a sand bypass system can do, and is from a technical memorandum of the USACE, regarding a study to the application of a sand bypass system in Port Hueneme, California, 60 years ago.

A sand bypass system, more specifically a fixed sand bypass system, due to the enormous amount of sand that is required to bypass to the downdrift beaches of those ports every year, has been into account many years ago. But a fixed sand bypass system in a wave climate as strong as the Portuguese wave environment can’t be built without thoroughly study all the possible alternatives. There are also mobile and semimobile systems using multiple types of dredgers which must also be taken into consideration to justify why the fixed system is the best solution.

5.1.2. FIXED SAND BYPASS SYSTEM IN PORTUGAL VS CURRENT SOLUTIONS

Fixed sand bypass systems are not as unusual as one may think. The first fixed sand bypass system is almost 100 years old and, even if the annual bypassed volume is way smaller than it would have to be in Portuguese cases, its efficiency is impressive. USACE, in 1930s decade, started to establish river inlets and immediately realized that something had to be done in order to allow the normal longitudinal sediment transport. That was how the first fixed sand bypass system was created and is still working after decades of use.

There is the same situation in Portugal, being the Aveiro Lagoon Mouth older than 200 years old, and with an accumulation problem updrift of the inlet since then. But the wave conditions in Portugal are much more severe than in Florida, USA, or in any other place where a system like this is implemented.
and this situation is constantly used to justify why a fixed sand bypass system had never been done in Portugal.

The accurate analysis contained in chapter 4 and the comparison between Portugal and other countries, where this kind of system is in use, can be extremely useful for the feasibility study.

Table 5.1 contains an overview of advantages and disadvantages of a fixed sand bypass system in a wave/weather environment like Portugal (Charlie Bicknel, 2006).

<table>
<thead>
<tr>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Relatively low running ongoing costs</td>
<td>Relatively high capital costs</td>
</tr>
<tr>
<td>Minimal disruption to beach users; no requirement to close large sections of the beach</td>
<td>The consequences in the updrift beach are uncertain</td>
</tr>
<tr>
<td>Bypassing can be undertaken at night to minimise visual impact at the disposal site</td>
<td>The need of a specialized team working during the hours of operation</td>
</tr>
<tr>
<td>Bypassing can be undertaken on a regular basis, throughout the year to prevent a large build-up of sand in the updrift beaches</td>
<td>The sand amount and properties are hard to control which can result in clogging of the system</td>
</tr>
<tr>
<td>Operational under most wave/weather conditions</td>
<td>The wave conditions of the places where fixed sand bypass systems are built are not similar to Portugal</td>
</tr>
</tbody>
</table>

The current operations for beach erosion mitigation in the adjacent areas of Aveiro and Figueira da Foz Ports are carried out by dredgers. Multiple works have been done during the last decades and consist of dredge multiple parts of the Ports navigational areas and placement in pre-determined locations. These locations were studied decades ago and are, supposedly, proven to be the most effective cost/consequence place to deposit sand and mitigate beach erosion downdrift of the ports. The costs to deposit sand in these places are relatively low but the effectiveness of this beach erosion mitigation is highly dubious. Since dredging operations are mainly carried out during winter time, the strong wave action cause an immediate movement of the sand downdrift of the placement area, instead of carrying the sand to the beach. Another important factor is the sand gradation: when the sand is thinner it tends to move right after it is placed but if the sand is larger, the tendency is to cause siltation in the placement area, and this must be considered when the sand placement area is decided. That said, there are no notorious improvements in the beaches where it was supposed to and beach profiles evolution along the last decade proves that. The endangered urban areas continue the same, both in Aveiro and Figueira da Foz, and definitive solutions are still being studied.

Since the sand bypass systems outlets can discharge directly at the beach, erosion mitigation is immediate with proven results in thousands of places around the world, unlike placement in immersed areas which has negative or inexisten results in several studied areas.
Studies were carried out in multiple Ports in India and the conclusion was that the method of dumping material offshore, on the assumption that the material would be moved onshore by wave action did not prove successful to safeguard the shoreline (K.G.S. Sarma, 2015).

On the other hand, dredging operations have multiple constraints both in operational hours, months per year or sand placement areas. Both due to Environmental Impacts constraints, tourism and wave conditions dredging operations can only be carried out during certain months of the year. Between January and April there is the lay of bivalves which impedes dredging operations. From June to September beaches are full of tourists and dredging is not permitted in order to not disturb recreational activities and tourism. After September the winter wave period starts and dredging boats are often unable to leave the Port protection berth due to strong wave action. With all these constraints, there are only 4 months of the year (May, June, September and October, considering a calm wave year) when dredging operations can be carried out freely and in perfect conditions. And even if the dredging operations are carried out during winter, taking advantage of relatively calm days, a severe storm can hit the coast the next day and the deposited sand will be easily taken from the original place and transported further south.

The bypass operations, in addition to work in any weather/wave conditions, can also work during night and cause no visual impact to be noticed in the morning after. This, even being bypass operations carried out mostly during winter, if an emergency discharge is needed during summer, it would create no constraints and the beach could be used in the day after.

Dredging works are only allowed during day time. It requires men to drive the boats which work in shifts of 4 hours, with 8 hours work per day. 4 hours can be enough for two trips if the sand placement location is offshore but, if placement directly at the beach is required, both time and costs would increase in an enormous rate.

Table 5.2 contains a comparison between dredging costs in Aveiro and Figueira da Foz (using suction dredgers) and cost of bypassing operations in Tweed River, Nerang River and Indian River.

<table>
<thead>
<tr>
<th>Year</th>
<th>Cost per cubic meter (€/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Dredging</td>
</tr>
<tr>
<td></td>
<td>Aveiro</td>
</tr>
<tr>
<td>2010</td>
<td>2.95</td>
</tr>
<tr>
<td>2011</td>
<td>1.72</td>
</tr>
<tr>
<td>2012</td>
<td>4.67</td>
</tr>
<tr>
<td>2013</td>
<td>2.56</td>
</tr>
<tr>
<td>2014</td>
<td>2.93</td>
</tr>
<tr>
<td>2015</td>
<td>2.83</td>
</tr>
<tr>
<td>2016</td>
<td>2.79</td>
</tr>
</tbody>
</table>

* The currency used from AUD and USD to Euro was 0.67 and 0.89, respectively, from 12/06/2017

By analyzing Table 5.2, is easy to admit that Nerang River bypass system is the most efficient and cheapest one to run. It seems like the cost of dredging and bypassing is comparable and such big investment as a sand bypass system would not be worth. But it is important to emphasize that the higher cost for Tweed River Sand Bypassing operations are due to its dimension (more than 7 km of
pipelines and all the associated cost: pumps, booster stations, etc) and extremely high volume of sand bypassed every year and Indian River only bypasses 80,000 m$^3$/year, which means that if bigger volumes were needed, system would be improved and those costs would be lower.

Nerang River is quite cheaper than dredging in Portugal and the most important thing is that sand obtained from dredging in Portugal is not deposited directly on the beach but in an offshore location. This offshore sand placement involve lower costs since the work is easier, it is not dependent on tide heights and times but, on the other hand, the efficiency of beach erosion mitigation is not even comparable.

That said, if dredging in Portugal started to involve sand placement directly on the beach, using pumps and pipeline systems for example, those 2, 3 or 4 €/m$^3$ could easily reach 10 €/m$^3$.

The possibility of the bypass system to operate in a regular basis is both an advantage and a disadvantage. It is a big advantage since it does not depend on the wave, weather or time conditions and does not allow a huge accretion of sand at the updrift beach. On the other hand, it requires a permanent team working both during day on maintenance and/or repair purposes and during night for supervision of the system. Nowadays all the fixed bypass systems have Programmable Logic Controller (PLC) systems that can automatically determine when to pump sand, with which pumps and can also stop the system if something wrong is happening. This automatic and programmable system allows workers to leave the work station during night and just be preventive if some emergency happens.

The fixed system is not only the most efficient, used when the annual bypassing rates are in the order of half a million cubic meters, but is also the most invasive method to mitigate beach erosion in the adjacent areas of river inlets/port infrastructures, and it must be considered (Richard Mocke et al., 2005).

A fixed sand bypass system and the infrastructures that it requires have a huge impact both in the longitudinal sediment transport and in the visual of the surrounding areas.

5.1.2.1. Aveiro Lagoon Mouth

São Jacinto, the updrift beach of Aveiro Port, is a natural reserve and consequently there are no infrastructures, either houses or recreational infrastructures, in the surrounding area where the jetty would be built.

An Environmental Impact Assessment is required but no impacts are expected, and in addition it would create an attractive place to visit, a place in which people could go for fishing, walking or surfing. The jetty, from the sand bypass system in Nerang River and Tweed River, constitutes nowadays an attraction for the Gold Coast tourists. It has a fixed price to go fishing up there and the way it was built, constituting a sand trap, created a great spot for surfing and consequently several surfers often cross the River Inlet to go surfing in an area where no surf existed before.

The same happens in São Jacinto: the northern breakwater constitutes a barrier not only for sand transport but also for wave action. The reflection effect creates a triangular wave pretty close to the breakwater which is an attraction for surfers that often cross the river to go surfing. The problem is the highly dynamic wave action that both accumulates hundreds of thousands of cubic meters of sand in the adjacent area of the northern breakwater, and removes the same amount of sand from that area. This situation is able to create several weeks of great surfing in São Jacinto but can also result in horrible sand banks which do not allow surf for months. The existence of the jetty structure, if the
system works in Portugal as it works in Australia, would create a barrier for wave action allowing a less dynamic sand movement in the adjacent area of São Jacinto and consequently, more consistent surfing conditions (to be tested in laboratory).

5.1.2.2. Figueira da Foz River Mouth

The problem of visual and environmental impact in Figueira da Foz is more complicated than in Aveiro case. On one hand Figueira da Foz city center is adjacent to coastline, where big habitational and office buildings are built, which could be negatively influenced by a huge structure out to sea (jetty structure). On the other hand, this beach, which could be a usually busy and crowded beach because of its perfect location being so close to the city center, is always empty and completely uncharacterized. Since the beach increased almost 200 m only in the last 6 years (years studied in this thesis and fully documented in chapter 3), it became impossible for people with reduced mobility or even to people that simply do not want to walk for 15 minutes in the sand to reach the sea, to go to this beach. Adjacent beaches, both north and south of Figueira da Foz got crowded in the last few years but have some limitations since at the same velocity that Figueira da Foz main beach increases year after year, southern beaches (downdrift of Figueira da Foz Port) have been decreasing.

The huge accretion of sand in Figueira da Foz Port updrift beach also brought big constraints to surf. Buarcos is the name of a parish in Figueira da Foz city but is also the name of the longest wave in Europe. It is usually compared with Jeffreys Bay in South Africa which is the most well-known long wave in the world and where a stage of the World Tour of Surfing is carried out.

Peniche, a city further south in Portugal, is where the Portuguese stage of the World Tour of Surfing is carried out and it guarantees revenues of almost 10 million € each edition. Curiously, the first World Surfing event in Portugal was in Figueira da Foz back in 1996. This world surfing event was carried out in Cabedelo beach, the first beach south of Figueira da Foz Port, which has been the biggest victim of the lack of sand reaching the downdrift side of the Port.

This would be the immediate advantage and impact that the sand bypass system would have in Figueira da Foz surf but Buarcos, the northern beach which breaks in a reef break, would also get advantages of the system since nowadays the reef is fully covered with sand, sand that should be moving to beaches further south of the Port.

5.2. EXISTING TYPES OF SAND BYPASSING SYSTEMS

Several alternative solutions must be identified and studied in order to understand which kind of bypass system would work better in Aveiro and Figueira da Foz environments. As presented in the first chapter, there are 3 possible types of sand bypass systems:

- Mobile Sand Bypass System;
- Semi Mobile Sand Bypass System;
- Fixed Sand Bypass System.

Layout drawings, explanation of each system operation and estimated costs of these 3 different systems were developed.

Before introducing Aveiro and Figueira da Foz Port solutions, a brief description of each one of these bypass systems was developed, considering multiple examples from Literature Table (Table 4.1, in chapter 4).
As seen in the statistical analysis of sand bypass systems around the world, United States of America is the country where most of the bypass systems are operating nowadays. Various solutions are available only in Florida, a state with hundreds of river inlets, where all the types of sand bypass systems are operating.

Since the necessary volumes to bypass are not as huge as they are in Australia, South Africa or even in California, weir jetties, and consequent creation of sandtraps, are one of the most used solutions. Then, sand is dredged from those sandtraps and transported until downdrift beaches for discharge.

The way used to transport the sand from the dredger to downdrift beaches is what varies the most.

5.2.1. MOBILE SAND BYPASS SYSTEM

Regarding Mobile Systems 3 examples were considered:

- Sand trapping breakwater, dredging of sand trap and sand placement in downdrift beaches;
- Sand transported by truck;
- Sand accumulation area in the updrift side of the Port and sand placement in downdrift beaches via floating pipeline/rainbow technique.

5.2.1.1. Fort Pierce Inlet, Florida, USA

The sand bypass system used in Fort Pierce Inlet, as shown in Figure 5.1, consists of a breakwater running parallel to the coast. It is attached to the updrift breakwater and the two breakwaters together form an extremely efficient sand trap.

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Fig. 5.1 – Schematic view of Fort Pierce Sand Bypass System
An average of 30,000 m³ has been placed in the downdrift side of the inlet each year. A suction dredger dredges the sand trap and the navigation channel and place it both in an offshore placement area or near the beach.

This sand trapping shape is very efficient considering how soft is the wave regime in Florida. A breakwater running parallel to the coast would be a big construction challenge to be built in the Portuguese coastline since the wave regime is one of the most aggressive in the whole world, as seen in the wave energy map in Figure 4.9.

5.2.1.2. Point Roberts Marina, Washington, USA

Point Roberts Marina is an artificial marina in the state of Washington. The marina was constructed using several innovative design concepts (Jeffrey A. Layton et al., 1991), as shown in Figure 5.2:

- Narrow entrance channel coupled with curvilinear basin geometry to promote hydraulic circulation;
- An annual sediment bypass operation to control downdrift shoreline erosion;
- The use of various coastal structures to protect the marina entrance channel from severe offshore wave activity. The performance of these design features, as well as other operational characteristics of the marina, are discussed in the paper.

Dredging is being done by mechanical equipment (bulldozers, backhoes, loaders, etc) operating at suitable low tides. Material from the eastern dredge site is trucked to disposal site and material from west site is directly carried to the adjacent disposal site.

![Fig. 5.2 – Schematic view of Point Roberts Sand Bypass System](image-url)
The sand dredged from the eastern side (right in the picture) is carried out by truck, to the downdrift western beach by truck. It is proven to be the most efficient and cheapest way to bypass sand from the updrift to the downdrift part of the marina entrance.

The difference between Point Marina Roberts and Aveiro, or Figueira da Foz Port, is that in Point Roberts the trucks only have to carry the sand for 1.5 km. In Aveiro, the only way for a truck to carry the sand from the updrift to the downdrift side of the Aveiro Lagoon Mouth is to drive for almost 60 km. In Figueira da Foz, it is not so far from one side to another side of the River Mouth but it is also 7 km, more than 4 times Point Roberts Marina situation. Only 8,000 m$^3$ of sand are bypassed each year by Point Roberts Marina sand bypass system.

5.2.1.3. Costa da Caparica, Portugal

Costa da Caparica is a civil parish located in the western coast of Setúbal, Portugal. It has been, like all the Portuguese coastline, buffered by huge storms and due to its geographic characteristics is nowadays one of the most endangered parts of the Portuguese coastline.

Back in 2007, during summer (July and August) and bathing season in Portuguese beaches, a dredging and beach nourishment through Floating pipeline was carried out in Costa da Caparica eroded beaches, as shown in Figure 5.3. During 2 months, 3 dredgers with different hopper capacities: 1,000, 3,000 and 5,000 m$^3$, were used to nourish of 1,000,000 m$^3$ of sand directly in the beach. That said, the unitary cost per cubic meter was 5 € (Agência Portuguesa do Ambiente, 2007). All the sand was dredged from the navigation channel of Tagus River.

Fig 5.3 – Schematic view of Beach nourishment though Floating Pipeline in Costa da Caparica (Rohde Nielsen, 2007)
5.2.1.4. Visakhapatnam, India

Sand bypass operations have been carried out in Visakhapatnam after the outer harbour was built between 1970 and 1975 (MVR Murthy, 2007). The project of this outer harbour envisaged the construction of a detached breakwater, having a gap between the western end and the south breakwater (left in the picture), to let the littoral drift sand into the sand trap area, as detailed in Figure 5.4.

A hopper sand dredger dredges sand from the sand trap area and carries it to downdrift beaches of the Port. This method allows the dredger to hold its position about 1.5 Nautical miles away from the coastline and discharge the mixture of sand and water to a distance of approximately 100 m. The material falls within the 0-6 meters’ contour (depending on the beach profile) (MVR Murthy, 2007).

The cycle time of the operation is 4.5 hours and at least 5 loads are pumped every day with cumulative quantities ranging from 20,000 – 22,000 m$^3$/day (MVR Murthy, 2007).

Even though this is a good method, due to the enormous draft of these kind of dredgers which stop them to go closer to the coastline and the maximum distance that the sand can be pumped, the erosion mitigation is not with direct beach nourishment.

The operations that are being carried out nowadays in Portuguese Ports of Aveiro and Figueira da Foz to mitigate beach erosion are the sand placement in depths between -2 and -8 m CD. This rainbow technique, considering that it uses the same kind of dredgers used in Portuguese cases, can only place sand 100 meters closer to the coast than what is being done.

The big advantage of this system is cost saving compared to floating pipeline technique. This technique not only dispensed the laying and maintenance of the pipeline but also reduces the time frame of each project.

Since both floating pipeline and rainbow technique are systems used in Visakhapatnam, there are two prices to compare (M.T. Krishna Babu, 2015):

- 200,000 m$^3$ via floating pipeline in December 2015: 7 €/m$^3$;
- 250,000 m$^3$ via rainbow technique in March 2014: 5€/m$^3$.
5.2.2. SEMI MOBILE SAND BYPASS SYSTEM

Semi mobile systems are the most used ones in the world. There are very similar cases to Aveiro or Figueira da Foz Ports situation. 4 cases were studied:

- Detached breakwater, trapping sand dredging of sand trap and sand placement in downdrift beaches through a pipeline system;
- Updrift breakwater trapping sand, dredging of sand trap, sand discharging in hopper system and placement in downdrift beaches through a pipeline system;
- Weir jetty, dredging of sand trap and sand placement in downdrift beaches through a pipeline system;
- Updrift breakwater trapping sand, dredging of sand trap and sand placement in downdrift beaches via rainbow technique.

5.2.2.1. Channel Islands Harbour, California, USA

Channel Islands Harbour sand bypass system is a very peculiar one for multiple reasons:

- Is responsible for the erosion mitigation caused by two adjacent ports (Channel Islands Harbour, to the left, in the picture, and Port Hueneme, to the right, in the picture);
- Contains a detached breakwater, as shown in Figure 5.5, which serves a dual function of sheltering the harbour entrance and acting as a longshore sediment transport sand trap.

The longshore sediment transport per year in California can go until 1,000,000 m$^3$ and the average bypassed volume per year is 800,000 m$^3$. 
This is probably the most similar situation in the world to the Portuguese situation regarding longshore sediment transport. The bypassed volume is even bigger than the necessary one in Portuguese ports: 400,000 m³ in Aveiro and 500,000 m³ in Figueira da Foz Port.

5.2.2.2. Port of Durban, Durban, South Africa

Port of Durban uses a unique method of sand bypassing. The port contains an updrift breakwater which serves as a sand trap which is later dredged by a suction dredger and placed in a hopper structure, as shown in Figure 5.6.

Inside of the Port, in a terminal adjacent to the water, there is a hopper system which has capacity for 3 dredgers loads: 5,500 m³. The biggest advantage of this system, comparing with any other semi mobile sand bypass system, is this particular capacity to get up to 3 dredgers loads. The efficiency gets so much bigger with this system that the annual sand bypassing target have been over-achieved. In 2016, the sand bypassed volume was 600,000 m³, more 100,000 than the established target.

![Diagram of Port of Durban sand bypass system](image)

Fig. 5.6 – Schematic view of Port of Durban sand bypass system

5.2.2.3. Hillsboro Inlet, Florida, USA

Hillsboro Inlet is one of the most successfully managed coastal inlets along the east coast of Florida. The hydraulic cutterhead dredger is owned by the District and dredges the navigation channel and the sand trap caused by the weir jetty in the updrift breakwater, as shown in Figure 5.7.

The sand bypass system works in a rate of 90,000 m³ per year since 1996 but, even though the efficiency of the system, the Hillsboro inlet is only 86 m wide when Aveiro Lagoon Mouth is 565 m and Figueira da Foz River mouth is almost 380 m wide. The challenge to dredge a navigational channel like Hillsboro is nothing comparing with the dimension of the two Portuguese River mouths.
5.2.3. Fixed Sand Bypass System

There are only 9 fixed sand bypass systems operating at the moment in the whole world, as shown in Table 4.1. It is natural to think that these, apparently, complex and very sophisticated systems are, maximum 10 or 15 year old. That is partially true. From those 9 systems, 4 are less than 25 years old but then there is one which is 27 years old, another one is 31 years old and then there are 2 systems in Florida which have more than 50 years.

3 types of fixed sand bypass systems were studied:

- Crane mounted jet pump in updrift beach and sand placement in downdrift beaches through a pipeline system, Figure 5.8;
- Crane mounted jet pump in a pump station in the updrift breakwater and sand placement in downdrift beaches through a pipeline system which is attached to a bridge, Figure 5.9;
- Jetty steel structure with 10 jet pumps, clear water intake, pump station and sand placement in multiple outlets in downdrift beaches through a pipeline system, Figure 5.10.
5.2.3.1. Indian River Inlet, Delaware, USA

![Schematic view of Indian River Sand Bypass System](image)

After more than 30 years of dredging operations in Indian River Inlet trying to keep the navigation channel in good conditions, in 1990 a fixed sand bypass system was built. Taking advantage of the existing conditions, the pipeline system was implemented using the bridge in the surrounding area, avoiding bigger costs burying the pipeline system.

Even though it is an efficient sand bypassing system, it only bypasses an average of 70,000 m³ of sand per year, due to its reduced longshore sediment transport of 150,000 m³/year, compared with the 1 million m³ of sand moving in the Portuguese littoral drift. Indian River system comprises a single jet pump which cannot provide the same bypassing rate as a system with 10 jet pumps (in the case of Tweed River Sand Bypass System, Australia).

5.2.3.2. Lake Worth Inlet, Florida, USA

Lake Worth Inlet is one of the four inlets which link the Intracoastal Waterway with the Atlantic Ocean in Palm Beach County. Those 4 inlets have each one a sand bypass system:

- Jupiter Inlet, operating since 1966, which consists of a weir jetty, a sand trapped dredged by a suction dredger and then a pipeline system discharging in downdrift beach in a rate of 60,000 m³/year;
- Lake Worth Inlet, operating since 1958, which consists of a crane mounted jet pump, in a pump station, located in the updrift breakwater, discharging through a pipeline system to downdrift beach, in a rate of 150,000 m³/year;
- South Lake Worth Inlet, operating since 1937, which consists of a crane mounted jet pump, in a pump station, located in the updrift breakwater, discharging through a pipeline system, via an existent bridge, to downdrift beach, in a rate of 45,000 m$^3$/year;
- Boca Raton Inlet, operating since 1980, consists of a system exactly like the one in Jupiter Inlet but in a rate of 40,000 m$^3$/year.

Lake Worth Inlet was the chosen system to be fully described since it is the one with the highest annual rate of sand placement. The sand transfer plant was constructed to bypass sand across the inlet when widening and deepening works were carried out in the inlet.
5.2.3.3. Tweed River Inlet, New South Wales, Australia

Tweed Sand Bypassing is a joint initiative of the New South Wales and Queensland State Governments. The project's objectives are to establish and maintain a safe, navigable entrance to the Tweed River and restore and maintain the coastal sand drift to the beaches on the southern Gold Coast of Queensland (Tweed Sand Bypassing, 2017).

The project is a big success due to its efficiency since the operations started in 2001. It consists of a steeled jetty in the updrift side of the River entrance, which contains hydraulically operated jet pumps, pumping sand from the sand trap created by the jetty, to the pump station and later through a pipeline system discharging in multiple outlets in downdrift beaches.

Even though the efficiency of this sand bypass system, the biggest challenge, comparing it with the Portuguese coastline, is the difference between the two wave regimes. Apart from that, 500,000 m$^3$, at least, have been bypassed every single year since the operations began, which is the pretty much the same volume required for Portuguese cases.
POSSIBLE SOLUTIONS OF SAND BYPASS SYSTEMS FOR AVEIRO AND FIGUEIRA DA FOZ PORTS

6.1. AVEIRO PORT POSSIBLE SOLUTIONS

Knowing how challenging is the Portuguese coastline comparing to most of the 55 sand bypass systems present in the literature review, regarding both wave regime, tide amplitude, necessary bypassing volumes per year, etc, appropriated solutions for Aveiro Port were studied.

In Aveiro Port case, 6 complete solutions were studied and costs were estimated. Considering all the restrictions imposed, the following systems were studied:

- Crane Mounted Jet Pump, pump station and discharging in downdrift beaches through a buried pipeline system;
- Weir jetty with corresponding sand trap and consequent dredging and discharging in downdrift beaches through a floating pipeline;
- Weir jetty with corresponding sand trap and consequent dredging and discharging in downdrift beaches through rainbow technique;
- Weir jetty with corresponding sand trap and consequent dredging and discharging in hopper system to later discharge in downdrift beaches via pipeline system;
- Weir jetty with corresponding sand trap and consequent dredging and discharging in downdrift beaches through a buried pipeline system;
- Fixed system composed by a steeled jetty, clear water intake, hydraulic jet pumps, pump station and discharging in downdrift beaches through a pipeline system.

Regarding the other possible sand bypassing solutions, they were not considered due to the following reasons:

Construction of a detached breakwater in such a place where wave energy accumulation is enormous would be not only a big challenge during the construction phase but also during the exploitation of the system. If a storm reaches the coast and the sand dredging operations has to be on hold during a week or two, the siltation of the navigation channel would be immediate and costs associated with an emergency dredging would not worth it. Schematic view of a system like this in Aveiro Port, shown in Figure 6.1.
Pump station in the updrift breakwater with correspondent crane mounted jet pump would be a challenging solution, represented in Figure 6.2. Trying to bypass 500,000 m$^3$ each year using a single jet pump is already a hard task to carry out, and attach it to a pump station in such an impact zone like the updrift breakwater in a wave regime like the Portuguese one would be even worse. This, associated with the fact that remove such a huge amount of sand from the adjacent area of a structure like the updrift breakwater would endanger the structure.
Bulldozers collecting sand from updrift beach and carry it to downdrift beaches via trucks would not worth it due to the distance from one side to another (60 km). The damages caused to the roads, considering that this would be a recurrent process, could be even bigger than the cost for transportation, Figure 6.3.

Construction of a sand trapping breakwater, running parallel to the coast, would also be a big challenge both during construction and operational phases, Figure 6.4. Due to the enormous volume of sand driving in the littoral drift, comparing to Fort Pierce Inlet, where a system like that is built, the sand trapping breakwater would have to be hundreds of meters long. Otherwise, the sand trapping efficiency would not be as desired, and sand would go through the sand trap and accumulate in the Lagoon Mouth anyway.

Fig. 6.3 – Schematic view of Bulldozers collecting sand and transportation by truck, Aveiro Port

Fig. 6.4 – Schematic View of Sand Trapping breakwater, Aveiro Port
6.1.1. CRANE MOUNTED JET PUMP IN THE UPDRIFT BEACH

6.1.1.1. Operation Cost Analysis

Indian River Sand Bypass System, shown in Figure 6.5, the one that can be used for direct comparison regarding this specific kind of sand bypass system, bypasses an average of 7,000 m$^3$ of sand every month. The sand bypass system was designed to deliver approximately 130 m$^3$/hour to downdrift beach. Considering that bypass operations are carried out 20 days per month, it gives an average of 350 m$^3$ per day. In such a complex and instable system like pumping sand subject to weather and wave conditions, the average of 130 m$^3$/hour is not always carried out.

![Fig. 6.5 – Crane Mounted Jet Pump in Indian River (Dan Brower, 2012)](image)

Then:

$$\text{Hours per day} = \frac{350}{130} = 2.69 \text{ hours}$$

The system works an average of 3 hours per day of operation.

If a system like this must bypass 400,000 m$^3$ every year, as intended in Aveiro Port situation, it has to pump sand in a daily rate higher than 3 hours.

In a rate like the one in Indian River, with 130 m$^3$ per hour, considering 8 months of operation every year, excluding summer time and one month of extreme wave conditions and impossibility of sand bypass operations, and 20 days per month, the required number of hours per day would be:

$$\text{Volume per month} = \frac{400,000}{8} = 50,000 \text{ m}^3$$

$$\text{Volume per day} = \frac{50,000}{20} = 2,500 \text{ m}^3$$
\[ \text{Hours of operation per day} = \frac{2,500}{130} = 19 \text{ hours} \]

Given that evidence, and considering that 19 hours of operation per day cannot reasonably be carried out, more jet pumps should be used.

Considering 6 hours as a reasonable workload per day (= 420 m\(^3\)/hour), the number of jet pumps to use would be 4:

\[ \text{Volume per hour} = \frac{2,500}{6} = 417 m^3 \approx 420 m^3 \]
\[ \text{Number of jet pumps} = \frac{420}{130} = 3.23 \approx 4 \]

The cost per cubic meter of sand bypassed in Indian River system is about 5.8 €/m\(^3\), taking into consideration that only one jet pump is used. The cost of operation includes the operation of the following component parts:

- Clear water intake pump from the river to pump station;
- High pressure water pump from pump station to jet pump;
- Crane mounted hydraulic jet pump;
- Slurry pump from pump station to discharge points downdrift.

In Aveiro Port situation, considering the larger necessary volume to bypass, all the components would have to be improved or used in a larger number and, consequently, the energy consumption would be much bigger. Even though the number of jet pumps would be four times higher than the original system, most of the systems do not necessarily consume four times more energy:

\[ \text{Cost} \approx 15 \frac{€}{m^3} \]

6.1.1.2. Construction Cost Analysis

For the construction of a system like this, considering that the pipeline system, instead of crossing the navigation channel through a bridge, as to be buried in the bottom of the navigation channel, material and workmanship associated for this work are:

- 1 Clear Water Intake Pump;
- 1 High Pressure Pump;
- 4 Jet Pumps;
- 1 Crane (based on Indian River Sand Bypass System, in which the crane is able to hold 150 tonnes and only carries 1 jet pump, the crane in this case would be a 600 ton crane). The cost was consulted in alibaba.com);
- Pipeline system;
- Booster station.

Wayne Jansen, Technical Supervisor of Sand Bypass System of Port of Ngqura, provided the work and quantities map of Port of Ngqura sand bypass system contract work. That is a contract work from 2007 and the costs were originally in South African Rand. The used exchange rate was:

\[ 1 \text{ South African Rand} = 0.0696720211 \text{ €} \]

Table 6.1 contains the total cost for the implementation of a Quadruple Crane Mounted Jet Pump System in Aveiro Port.
The enormous cost of construction of a system like this, mainly due to the cost of the crane, which would have to support 4 jet pumps, does not worth it. Figure 6.6 shows a schematic view of a system like this in Aveiro Port. A fixed structure, like a jetty, would accommodate the 4 jet pumps more safely and for a relatively similar construction cost.

![Schematic view of Aveiro Port](image)

**Fig. 6.6 – Schematic view of Aveiro Port with a Quadruple Crane Mounted Jet Pump System**

### 6.1.2. Weir Jetty and Sand Placement Through Floating Pipeline Technique

#### 6.1.2.1. Construction Cost Analysis

This is a kind of system involving a hopper section dredger, which can be, like in Durban’s case, a dredger with a length up to 89 m, containing a big hopper which can load up to 1,600 m$^3$ of sand, and a total cost of dozens of millions of Euros.
The initial investment would be huge and would not be worth it if it is just to use in one Port and in a sporadic way. But if it was a co-investment from two or three Port Authorities, permanent sand bypassing operations could be carried out in several River Mouths and erosion mitigated. An operation like this was already carried out in Costa da Caparica, in the southern shore of Lisbon, in 2007 and 1 million cubic meters were placed directly in the beach, at a cost of 5 €/m³. Visakapatnam Port Authority carried out operations like this every year to mitigate beach erosion downdrift of its Port, as shown in Figure 6.7.

![Image](image_url)

**Fig. 6.7 – Floating Pipeline Technique in Visakapatnam, India (thehindu.com)**

The creation of the weir jetty would be basically a lowering operation of the existent breakwater, in a length of one or two hundred meters, of the northern breakwater. This would allow not only the passage of sand into a sandtrap, which would subsequently be dredged, but also the prevention of navigation channel siltation since the sand would not go further than the sandtrap (physical and numerical modelling are required to prove this hypothetical sand dynamics).

The cost of the weir jetty, which is simply the controlled destruction of a part of the northern breakwater of Aveiro Port, was calculated, primarily based on Figure 6.8.
Assuming the length of the weir jetty as 200 m, using the dimensions detailed in Figure 6.8, and the price per cubic meter of “destruction”, and subsequent finishing, as 200 €, based on evaluation of existent works carried out in Aveiro Port, the total cost of the weir jetty would be:

\[
Total \ text{volume to remove} = 6 \times 2 \times 200 = 2,400 \text{ m}^3
\]

That said, the total cost of the jetty would be:

\[
Total \ text{cost of the jetty} = 2,400 \times 200 = 480,000 \text{ €}
\]

6.1.2.2. Operation Cost Analysis

Based on Costa da Caparica’s sand bypassing experience, using a hopper dredger and floating pipeline technique, the cost per cubic meter would be: 5 €/m³.

Or based on the Indian operation cost: 7 €/m³.
6.1.3. WEIR JETTY AND SAND PLACEMENT THROUGH RAINBOW TECHNIQUE

This kind of system involves the same works as the one using floating pipeline system but the operational costs are lower. Visakapatnam Port Authority, also uses this technique in some years’ operations and is proved to be less expensive. The biggest problem of this method is the enormous visual impact, as shown in Figure 6.9.

6.1.3.1. Operation Cost Analysis

Based on the cost of Visakhapatnam from 2014:

\[ \text{Cost} = 5 \text{ €/m}^3 \]

6.1.3.2. Construction Cost Analysis

It involves the reconfiguration of a part of the northern breakwater, in order to turn it into a weir jetty and a hopper dredger with a rainbow pumping system incorporated.

Total Cost of Northern Breakwater reconfiguration= 480,000 €.

A schematic view of a system like this in Aveiro Port is detailed in Figure 6.10.
6.1.4. Weir Jetty and Sand Placement in Hopper System to Later Discharge Through Pipeline System

Port of Durban has a system which consists of dredging a sand trap adjacent to the updrift breakwater and then discharging sand to a hopper system with subsequent sand placement via pipeline system. Due to the wave regime in the Portuguese coastline, this solution was adapted using a weir jetty instead of dredging the updrift side of the updrift breakwater. The dredger must have an over-the-side connection to connect to the land based hopper system. Adjacent to the hopper system, there is a pump station and a similar system like the one in Indian River, for example.

The biggest problem of this system is the distance between port facilities, where the hopper can be built, and available berths to discharge outlets. In Port of Durban, the berth where the hopper facilities are installed is close to the beach but in Aveiro Port situation, the closest available berth is more than 2 km away from the discharge outlet, as shown in Figure 6.11.

This will increase both the construction and operation costs. Calculations are developed further.
6.1.4.1. Construction Cost Analysis

Due to physical and wave related restraints that would have to build any kind of sand trap in the updrift beach of Aveiro Port, a weir jetty was considered, instead of a sand trap like in Channel Islands Harbour or Fort Pierce Inlet.

The weir jetty associated cost is the same as studied before and the hopper dredger, provided with an over-the-side connection, to direct connect to the land hopper structure. Pipeline system, with no less than 3,000 m, considering HDPE, PN10 and DN450 pipelines would cost: 1,500,000 €, including installation and accessories.

The hopper structure must also have a pump station with a slurry pump, which provides a flow of 3,000 m³/hour, with a maximum of 25 % of sand (50,000 €, according to José Ruas, owner of a dredger construction company in Aveiro, Portugal).

Due to the enormous length of the pipeline system, apart from the slurry pump which has a maximum reach of 1,000 m, at least two booster pump would be necessary. Considering the price of 43,000 €/booster station, like the ones used in Port of Ngqura, the system would cost much more than in the South African case.

The resume of the construction costs are as follow:

- Weir jetty: 480,000 €
- Hopper dredger (rented);
- Pipeline System: 1,500,000 € (as shown further in Table 6.6);
- Slurry pump: 50,000 €;
- Booster Station: 43,000 €;
Hopper Structure: to be calculated, but an estimated cost of 1 million € was defined. A schematic view of its function is represented in Figure 6.12.

\[ TOTAL \ COST = 3,073,000 \ € \]

6.1.4.2. Operation Cost Analysis

Based on the cost of Port of Durban Sand Bypass system from 2016:

\[ Cost = 3.6 \ €/m^3 \]

Given that the hypothetical Portuguese system would have a pipeline system with, at least, 4 times the size than the Port of Durban system, and all the associated costs that those accretions imply, this kind of system in Aveiro Port could easily cost up to 10 €/m³.

Fig. 6.12 – Schematic view of Sand Hopper System Operation (iol.co.za, 2017)

6.1.5. WEIR JETTY AND SAND PLACEMENT DOWNDRIFT THROUGH PIPELINE SYSTEM

In the last few years the dredging of Aveiro Port navigation channel and Outer Basin has been a recurring operation but the dredging of that volume would not be enough for beach erosion mitigation. Considering the last 7 years:

- 2010: no dredging of the navigation channel or outer basin;
- 2011: 70,000 m³ of sand were dredged from the navigation channel;
- 2012: no dredging of the navigation channel or outer basin;
- 2013: 1.5 million m³ of sand were dredged from the navigation channel but all this volume was only due to the deepening works;
- 2014: 360,000 m³ of sand were dredged from the navigation channel;
- 2015: 175,000 m³ of sand were dredged from the navigation channel;
- 2016: 100,000 m³ of sand were dredged from the navigation channel.

By counting only the normal years, excluding both 2010 and 2012 when no dredging operations were carried out and 2013 when abnormal quantities were dredged, the average amount of dredging of navigation channel per year in Aveiro Port is 175,000 m³.
This volume, 175,000 m$^3$, can be easily dredged by a suction dredger (like the one in Figure 6.13) and directly place the sand downdrift via an incorporated floating pipeline system. Knowing that the volume dredged by the navigation channel would not be enough to minimally mitigate beach erosion, a weir jetty would be built and the creation of a sand trap would provide enough sand to bypass and, consequently, mitigate beach erosion downdrift.

A dredger like that could be bought by Aveiro Port Authority and dredge all the Port Areas but, since most of Port Areas contain contaminated and inappropriate sand for beach nourishment, this could not be a reliable way for erosion mitigation purposes.

The cost estimation is developed further.

6.1.5.1. Construction Cost Analysis

José Ruas, managing partner of a Dredger Construction company named “José Ruas, Shipbuilding” builds dredgers (like the one in Figure 6.12), fully equipped to bypass in a rate of 3,000 m$^3$/hour, 25% sand, maximum, and pump it via floating pipeline to a distance of 1,000 m. This kind of dredger costs 1,500,000 € and could easily fulfil navigation channel and weir jetty sand trap dredging purposes. This system, to operate in Aveiro like the conditions of Figure 6.14, would also need a booster station.

Due to its dimensions and instability, it is only able to navigate in very calm waters, where no waves break. A dredger like this could only operate inside port areas, protected from wave action.

$$TOTAL\ COST = 2,023,000\ €$$

6.1.5.2. Operation Cost Analysis

Knowing that the sand content during pumping operations is, maximum, 25%:

$$Sand\ pumping\ rate = 3,000 \times 0.25 = 750\ m^3/hour$$

Considering shifts of 8 hours per day:
Pumped volume of sand per day = 750 * 8 = 6,000 m³/day

Pumping 6,000 m³ of sand every day, expecting to dredge, every year, not only the accumulated volume in the updrift breakwater (400,000 m³) but also the required volume of sand for navigation channel maintenance:

\[
\text{Number of days of dredging operations} = \frac{175,000 + 400,000}{6,000} = 96 \text{ days}
\]

Considering the working time as 20 days per month, these operations would require, at least, 5 months (96/20 ≈ 5) per year to be completed. Once the floating pipeline, in order to not interfere with navigation purposes of Aveiro Port, would have to be buried in the navigation channel, the distance reached by the sand would not be the same. That said, a booster station (approximately 43,000 €) would be necessary and higher costs would be associated. Figure 6.14 contains a schematic view of a sand bypass system like this in Aveiro Port.

Regarding fuel costs, according to José Ruas, the fuel consumption of a dredger like this, with the pumping system operations, is 300 L/hour of diesel. Considering the price of 0.8 €/Liter, and the rate of 750 m³/hour, the total cost of each cubic meter of sand would be:

\[
\text{Cost} = \frac{300 \times 0.8}{750} = 0.32 \text{ €/m}^3
\]

6.1.6. JETTYS HOUSING JET PUMPS, PUMP STATION CONNECTED TO A CLEAR WATER INTAKE AND PIPELINE SYSTEM WITH MULTIPLE DISCHARGE LOCATIONS

Due to the necessary volumes to fulfil beach erosion in the downdrift beaches of Aveiro Port, around 400,000 m³ per year, the fixed solution composed by a steeled jetty and a complete pump station with
multiple discharge locations, which could go until the last groin of Costa Nova groin field (in a possible Aveiro Sand Bypass System) was always the most wanted one.

Doing a strictly direct comparison between Portugal and the associated costs of this kind of structure in other countries (Australia, South Africa or Japan) seems totally wrong due to the differences between wave regimes of Portugal and most of the other parts of the world. Tweed River Jetty structure is represented in Figure 6.15.

![Image](https://example.com/jetty STRUCTURE.jpg)

**Fig. 6.15 – Jetty Structure in Tweed River Sand Bypass System (coastalwatch.com)**

South African case of Port of Ngqura was built in 2007 and the cost for the jetty structure was approximately 1.9 million €. As seen in the world map of Wave Energy, the wave energy of South Africa is relatively similar to the Portuguese one and, from there, the structural design of a jetty structure in Aveiro Port updrift beach was developed.

By analysing the work and quantities map, it was found that the diameter of the jetty piles was D=760 mm. Due to the differences between Aveiro and Ngqura wave regimes, like seen in Figure 4.10 from Chapter 4, the admitted Diameter of the piles was 1,000 mm.

Figure 6.16 contains a sketch of the side elevation of the jetty structure, using the beach profile evolution in São Jacinto beach, updrift of Aveiro Port northern breakwater, and was how the first variables for the jetty design were taken.
6.1.6.1. Construction Cost Analysis

According to structural techniques, the maximum beam to consider must not exceed 10 meters. Another important feature is the length of the jetty. Taking into consideration that the closure depth in Aveiro Port updrift beach is 1,400 m and by analysing the beach profile featuring the side elevation of the structure, it was concluded that the length can go from 400 until 900 m in length. As the structure gets longer the cost also increases, and for that reason the length of 500 m was considered for the preliminary study developed further.

The buried part of each pile is one of the most important variables of the design and the best method to determine the lateral soil resistance for sand, to start a structural design of the jetty, is described in a paper from American Petroleum Institute: “Recommended Practice for Planning, Designing and Constructing Fixed Offshore Platforms - Working Stress Design” (COPYRIGHT 2003; American Petroleum Institute).

Figure 6.17 contains a graph which gives the initial modulus of subgrade reaction as function of angle of internal friction, \( \varphi' \). The initial modulus of subgrade reaction (k) is the value used to determine the strength of each spring, depending on distance to the mudline and distance of influence. Each spring and its strength associated value is used to simulate sand action when using a structural design software.
In Aveiro Port Jetty structural design, the sand considered, and its corresponding value of $k_{soil}$, was Sand below the water table, with an angle of internal friction of $35^\circ$ ($\phi'$), which gives a $k_{soil}=75 \text{ lb/in}^3$.

\[
1 \text{ lb/in}^3 = 271.45 \text{ KN/m}^3
\]

\[
75 \text{ lb/in}^3 = 20358.54 \text{ KN/m}^3
\]

After that, for the structural design software, a spring every half a meter was considered, for the buried depth of 5 m, and those values of Spring Strength ($K$), depend on depth ($x_i$) and distance of influence ($d_i$):

\[
K = k_{soil} \times d_i \times x_i
\]

When the pile is buried, due to the instability caused by the clumping equipment, the upper soil lost its properties and, according to Bowles, one must multiply the first value of Spring Strength ($K$) by 0.75 (Bowles, J. E., 1988).

Due to environment constraints, as it is a maritime structure, concrete and steel must have certain properties to resist to corrosive action of salt water.

Steel must be S275 ($\rho=77 \text{ KN/m}^3$) and Concrete C35/45 ($\rho=25 \text{ KN/m}^3$) as it is explained in Eurocode 2 (EC2). According to the first part of EC2, page 57, when a structure is built in places subject to tide and wave action and maritime breeze, the concrete must be C35/45 (page 233).
When designing a structure which will have to support truck loads or even crane load during the construction phase, as said in EC0 (page 47) and EC1 (page 26), the live load must be 5 KN/m.

Figure 6.17 and Figure 6.18 contain the multiple sections used for the calculation of the structure:

- Cross-section of the piles (Figure 6.18);
- Cross-section of the beams (Figure 6.19).

Regarding application of forces acting on a jetty structure, the calculations were based on a paper from Hilmesh B. Chopra et al., 2015 called “Application of Forces Acting on Jetty Structure”.

Tables 6.2 to 6.4 contain all the formula and admitted values which lead to the determination of all the forces acting on the jetty structure:

- Wave Force ($F_{DM}$, drag force + $F_{IM}$, inertia force);
- Dead Load (piles, beam and deck);
- Wind Force (for maximum wind speed of 40 m/s).

**Table 6.2 – Wave force calculation**

<table>
<thead>
<tr>
<th>Wave Force = $F_{DM} + F_{IM}$</th>
<th>$F_{DM}=0.5<em>C_D</em>p<em>D</em>H^2*K_{DM}$</th>
<th>54,45</th>
</tr>
</thead>
<tbody>
<tr>
<td>$F_{IM}=0.5<em>C_D</em>p<em>D</em>H^2*K_{IM}$</td>
<td>81,52</td>
<td></td>
</tr>
<tr>
<td>$C_D$ – Hydrodynamic force coefficient</td>
<td>0,53</td>
<td>$C_D$</td>
</tr>
<tr>
<td>$p$ – Density of seawater</td>
<td>10,27</td>
<td>$p$</td>
</tr>
<tr>
<td>$D$ – Diameter of pile</td>
<td>1</td>
<td>$D$</td>
</tr>
</tbody>
</table>
Table 6.3 – Dead Load calculation

<table>
<thead>
<tr>
<th>Pile</th>
<th>Beam</th>
<th>Deck</th>
</tr>
</thead>
<tbody>
<tr>
<td>688.75</td>
<td>31.25</td>
<td>625</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>L – Length of porch influencing area</th>
<th>A&lt;sub&gt;concrete&lt;/sub&gt; – Area</th>
<th>A&lt;sub&gt;steel&lt;/sub&gt; – Area</th>
<th>( \rho )&lt;sub&gt;concrete&lt;/sub&gt; – Density</th>
<th>( \rho )&lt;sub&gt;steel&lt;/sub&gt; – Density</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>0.64</td>
<td>0.15</td>
<td>25</td>
<td>77</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>B</th>
<th>H</th>
<th>B</th>
<th>L</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>0.6</td>
<td>5</td>
<td>10</td>
</tr>
</tbody>
</table>

Dead Load (KN) = 1345.00 At middle point of the porch.

Table 6.4 – Wind Load Calculation

<table>
<thead>
<tr>
<th>Vz (m/s) – Wind speed</th>
<th>Wind force (KN/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>40</td>
<td>0.96</td>
</tr>
</tbody>
</table>

Wind force = 0.6 * Vz^2

Wind force (KN/m) 0.96 Above the mean sea level.

Figure 6.20 contains all the loads and forces acting on the porch structure, which was the base to start the structural design.
These calculations and the structural review developed in software “MIDS GEN”, which showed that the structure like it was introduced was alright to receive the defined load, was a good indication of what should be the diameter of each pile of the jetty structure. From now on, the Diameter of the piles will be considered 1000 mm due to this revision. Report confirming the resistance of the system with the detailed characteristics, from software MIDAS GEN, is shown in the Appendixes.

Due to the complexity of a system like a sand bypass system, and all the structural calculations and details, the estimated cost for construction of Aveiro Port sand bypass system was based in the map of works and quantities of Port of Ngqura Sand Bypass System.

That system involved three major works:

- Preliminary and General;
- Marine Works;
- Mechanical, Electrical, Civil and Building Works.

The preliminary and general works consist of all the preparation works before the construction of the system. It requires preparation of the construction site itself, facilities for workers, offices, storage sheds, laboratory, etc. In the case of Port of Ngqura construction, it costed 1,500,000 €.

Marine works consist of Intake structure, Sand trap and Jetty and had a total cost of 1,900,000 €.

The last and the most important part is regarding the pump system. It involves pump station, booster station, pipelines and, finally, the training.

A direct comparison between this and the Portuguese case, Aveiro Port, can’t be done due to some differences, like detailed in Table 6.5.

Table 6.5 – Comparison between Aveiro and Port of Ngqura Bypass features

<table>
<thead>
<tr>
<th>Ngqura</th>
<th>Aveiro</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

132
<table>
<thead>
<tr>
<th></th>
<th>Aveiro</th>
<th>Ngqura</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length (m)</td>
<td>500</td>
<td>225</td>
</tr>
<tr>
<td>Piles Diameter (mm)</td>
<td>1,000</td>
<td>760</td>
</tr>
<tr>
<td>Deck elevation (m CD)</td>
<td>+ 9 m</td>
<td>+ 8 m</td>
</tr>
<tr>
<td>Pipeline System (m)</td>
<td>3,000</td>
<td>3,800</td>
</tr>
<tr>
<td>No. of Jet pumps</td>
<td>10</td>
<td>6</td>
</tr>
<tr>
<td>Maximum Volume to Bypass (m^3/year)</td>
<td>400,000</td>
<td>320,000</td>
</tr>
</tbody>
</table>

Taking into account the differences between the two systems:
- Length of the jetty is more than twice in Aveiro than in Ngqura;
- Due to environment characteristics, the Diameter of the piles must be 1,000 mm instead of 760;
- Higher deck elevation due to the possible wave height to hit the structure;
- Shorter length of the pipeline system, but in Aveiro Port case, there are at least 400 m of the pipeline which is buried in the navigation channel;
- Higher number of jet pumps, considering the highest volume to bypass each year.

Table 6.6 contains cost differences that the modifications between Aveiro and Ngqura Sand Bypass System would cause, based on Table 6.5.

<table>
<thead>
<tr>
<th></th>
<th>Aveiro</th>
<th>Ngqura</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jetty</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Length (m)</td>
<td>500</td>
<td>225</td>
</tr>
<tr>
<td>Diameter of the piles (mm)</td>
<td>1,000</td>
<td>760</td>
</tr>
<tr>
<td>Deck elevation (m CD)</td>
<td>9</td>
<td>8</td>
</tr>
<tr>
<td>Pipeline System (m)</td>
<td>3,000</td>
<td>3,800</td>
</tr>
<tr>
<td>No. of Jet pumps</td>
<td>10</td>
<td>6</td>
</tr>
<tr>
<td>Volume to Bypass (m^3)</td>
<td>400,000</td>
<td>320,000</td>
</tr>
<tr>
<td>Clear Water Intake</td>
<td>60,000</td>
<td>45,000</td>
</tr>
</tbody>
</table>

Considering the difference of cost as 3 Million €, the total cost for a fixed sand bypass system in Aveiro Port, with the objective to bypass 400,000 m^3/year with a jetty 500 m long would be, approximately, 9,200,000 € (total cost of Ngqura sand bypass system: 6,200,000, + 3,000,000 €).

6.1.6.2. Operation Cost Analysis

Costs regarding Sand Bypassing operations in Port of Ngqura are not available due to its instability of bypassed volumes per year, as shown in Table 4.7 from Chapter 4. 2015 was the best year and the bypassed volume was 182,000 m^3, even though the target volume is 320,000 m^3. The worst year was the first one with only 18,800 m^3. Multiple operational problems caused this instability and operational costs were never counted.
Tweed River and Nerang River sand bypass systems are the best ones to establish an indicative price per cubic meter bypassed.

Table 6.7 contains the most important differences between Aveiro Lagoon Mouth and Nerang and Tweed River entrances.

<table>
<thead>
<tr>
<th></th>
<th>Sand Bypass Volume (m3/year)</th>
<th>Length of the pipeline system (m)</th>
<th>Length of the jetty (m)</th>
<th>No. Of Jet Pumps</th>
<th>Cost per cubic meter (€/m3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nerang River</td>
<td>500,000</td>
<td>1,400</td>
<td>500</td>
<td>10</td>
<td>0.85</td>
</tr>
<tr>
<td>Tweed River</td>
<td>500,000</td>
<td>7,100</td>
<td>450</td>
<td>10</td>
<td>6.18</td>
</tr>
<tr>
<td>Aveiro Port</td>
<td>400,000</td>
<td>3,000</td>
<td>500</td>
<td>10</td>
<td>??</td>
</tr>
</tbody>
</table>

Nerang River operational costs are extremely low due to the simplicity of the system. The length of the pipeline system is much lower than Tweed’s case and the system suffered a lot of interventions during its lifetime which increased its efficiency to the point it is nowadays.

Aveiro Port case will not have the operational costs of Tweed River due to its shorter pipeline system and, consequently, the biggest simplicity of the system (as shown in Figure 6.21). Instead of 7 km of pipelines with completely different discharge points, it would have a unique pipeline direction with outlet in certain points along the coastline. As simpler as the system gets, number of booster stations is lower, pipelines’ associated costs are lower, less energy consumption and smaller team with less expenditure in salaries.

Fig. 6.21 – Schematic view of a Fixed Sand Bypass System in Aveiro Port
Using some simple calculations, the cost per cubic meter bypassed in Aveiro Port Sand Bypass System would be:

\[
7,100 - 1,400 = 5,700 \text{ m} \\
6.18 - 0.85 = 5.33 \text{ €} \\
7,100 - 3,000 = 4,100 \text{ m}
\]

That said, the cost per cubic meter of sand to bypass in Aveiro Port sand bypass System would be:

\[
\text{Cost per cubic meter} = 6.18 - \frac{4,100 \times 5.33}{5,700} = 2.35 \text{ €/m}^3
\]

6.2. FIGUEIRA DA FOZ PORT POSSIBLE SOLUTIONS

Considering how similar is Aveiro and Figueira da Foz Ports configuration, and being both in the same wave environment, the inviable systems regarding Aveiro situation will not be considered for a possible Figueira da Foz Sand Bypass System.

6.2.1. CRANE MOUNTED JET PUMP IN THE UPDRIFT BEACH

6.2.1.1. Operation Cost Analysis

In Aveiro Port possible sand bypass systems analysing, it was concluded that the single crane mounted jet pump was not enough for the necessary volume to bypass each year. In Figueira da Foz Port situation the necessary volume is even bigger: 500,000 m\(^3\)/year instead of 400,000 m\(^3\).

The same calculations developed for Aveiro situation are now developed for Figueira da Foz:

Like in Aveiro situation, where it was calculated that the possible system in Aveiro would have to work more than 3 hours per day, in Figueira da Foz situation, due to the highest volume, the hours of operation are even bigger.

If the flow is the same as in Indian River, 130 m\(^3\)/hour, considering 8 months of operation every year, excluding summer time and one month of extreme wave conditions and impossibility of sand bypass operations, and 20 days per month, the required number of hours per day would be:

\[
\text{Volume per month} = \frac{500,000}{8} = 62,500 \text{ m}^3 \\
\text{Volume per day} = \frac{62,500}{20} = 3,125 \text{ m}^3 \\
\text{Hours of operation per day} = \frac{3,125}{130} = 24 \text{ hours}
\]

Given that evidence, and considering that 24 hours of operation per day cannot reasonably and physically be carried out, more jet pumps should be used.

Considering 6 hours as a reasonable workload per day (≈ 420 m\(^3\)/hour), the number of jet pumps to use would be 4:

\[
\text{Volume per hour} = \frac{3,125}{6} = 520.8 \text{ m}^3 \approx 520 \text{ m}^3
\]
\[ \text{Number of jet pumps} = \frac{520}{130} = 4 \]

The cost per cubic meter of sand bypassed in Indian River system is about 5.8 €/m$^3$, taking into consideration that only one jet pump is used. The cost of operation includes the operation of the following component parts:

- Clear water intake pump from the river to pump station;
- High pressure water pump from pump station to jet pump;
- Crane mounted hydraulic jet pump;
- Slurry pump from pump station to discharge points downdrift.

In Figueira da Foz Port situation, considering the larger necessary volume to bypass, all the components would have to be improved or used in a larger number and, consequently, the energy consumption would be much bigger. Even though the number of jet pumps would be four times higher than the original system, most of the systems do not necessarily consume for times more energy:

\[ \text{Cost} \approx 15 \text{ €/m}^3 \]

### 6.2.1.2. Construction Cost Analysis

Since the required equipment is exactly the same as in Aveiro situation, excepting the length of the pipeline system, the total cost for the construction is detailed in Table 6.8.

<table>
<thead>
<tr>
<th>Units</th>
<th>Unitary Cost (€)</th>
<th>Total Cost (€)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clear Water Intake Pump</td>
<td>1</td>
<td>46,000</td>
</tr>
<tr>
<td>High Pressure Pump</td>
<td>1</td>
<td>43,000</td>
</tr>
<tr>
<td>Jet pump</td>
<td>4</td>
<td>70,000</td>
</tr>
<tr>
<td>Crane</td>
<td>1</td>
<td>4,000,000</td>
</tr>
<tr>
<td>Pipeline System (m)</td>
<td>2,000</td>
<td>100</td>
</tr>
<tr>
<td>Booster Station</td>
<td>1</td>
<td>43,000</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Even though the length of the pipeline system is lower in Figueira da Foz Port than it would be in Aveiro Port, the total construction cost does not change that much due to the cost of the crane.

Schematic view of the quadruple crane mounted sand bypass system in Figueira da Foz is represented in Figure 6.22.
6.2.2. **WEIR JETTY AND SAND PLACEMENT THROUGH FLOATING PIPELINE TECHNIQUE**

6.2.2.1. Construction Cost Analysis

Similar to Aveiro. Admitting that the only construction cost would be the weir jetty, according to calculations developed before:

Total cost= 480,000 €

Figure 6.23 contains the schematic view of this type of bypass system in Figueira da Foz Port.

6.2.2.2. Operation Cost Analysis

Similar to Aveiro. Cost per cubic meter= 5 €/m³ comparing to the Costa da Caparica case, from 2007, or 7 €/m³ comparing to Indian case, from 2015.
6.2.3. **Weir Jetty and Sand Placement Through Rainbow Technique**

6.2.3.1. Construction Cost Analysis

Similar to Aveiro.

Total cost of weir jetty = 480,000 €

A schematic view of Rainbow Technique as erosion mitigation in Figueira da Foz Port is represented in Figure 6.24.

6.2.3.2. Operation Cost Analysis

Based on the cost of Visakhapatnam from 2014:

\[
	ext{Cost per cubic meter} = 5 \, \text{€/m}^3
\]
6.2.4. Weir Jetty and Sand Placement in Hopper System to Later Discharge through Pipeline System

Unlike Aveiro Port situation, in Figueira da Foz, the most urbanized area is the northern one and there are several available berths in the southern shore of the river to the construction of a hopper facility, as shown in Figure 6.25. Like in Port of Durban situation, the distance between the hopper structure and the first discharge outlet is 600 m.

6.2.4.1. Construction Cost Analysis

Considering that the system would comprise any additional booster station that the one in Durban sand bypass system, and taking into account the calculations carried out for Aveiro Port situation (considering one less booster station than in Aveiro situation, 43,000 €):

\[ \text{TOTAL COST} = 3,030,000 \, \text{€} \]

6.2.4.2. Operation Cost Analysis

Based on the cost of Port of Durban from 2016:

\[ \text{Cost per cubic meter} = 3.6 \, \text{€/m}^3 \]

Due to Figueira da Foz similarities, regarding a hypothetical sand placement to a hopper system and discharging through pipeline system in downdrift beaches, to Port of Durban, the cost of operation can be considered the same.
6.2.5. Weir Jetty and Sand Placement Downdrift Through Pipeline System

Dredging of Navigation Channel and Outer Basin in Figueira da Foz happens quite more often than in Aveiro. Since the deepening works were not carried out yet, and due to the extremely fast siltation of the River Mouth, emergency dredging operations are usually carried out, even in supposedly not permitted periods of the year.

By analyzing the last 7 years’ records:

- 2010: 50,000 m$^3$ of sand were dredged from the River Mouth;
- 2011: 178,000 m$^3$ of sand were dredged from the River Mouth and Outer Basin;
- 2012: 100,000 m$^3$ of sand were dredged from the River Mouth and Outer Basin;
- 2013: 255,629 m$^3$ of sand were dredged from the River Mouth and Outer Basin;
- 2014: 110,000 m$^3$ of sand were dredged from the River Mouth and Outer Basin;
- 2015: 240,733 m$^3$ of sand were dredged from the River Mouth and Outer Basin;
- 2016: 270,000 m$^3$ of sand were dredged from the River Mouth and Outer Basin.

Aveiro Port has multiple navigation channels and the sand which comes from Vouga River does not necessarily reach the main navigation channel or the Lagoon Mouth.

It is also important to take into consideration the fact that Mondego River, the one that ends in Figueira da Foz Port, transports an annual amount of 80,000 m$^3$ of sand. This is even more important if we consider that this same amount of sand transported by Mondego River, before all the dams in its waterway were built, was 230,000 m$^3$/year.

That said, dredging of maneuver basin and adjacent areas of Multipurpose terminal, will also be considered for the calculation of necessary bypassing volumes.
The last 7 year were considered:

- 2010: no dredging of maneuver basin or Adjacent areas of Multipurpose terminal;
- 2011: 232,000 m³ of sand were dredged from maneuver basin and Adjacent areas of Multipurpose terminal;
- 2012: no dredging of maneuver basin or Adjacent areas of Multipurpose terminal;
- 2013: no dredging of maneuver basin or Adjacent areas of Multipurpose terminal;
- 2014: 107,000 m³ of sand were dredged from maneuver basin and Adjacent areas of Multipurpose terminal;
- 2015: 182,267 m³ of sand were dredged from maneuver basin and Adjacent areas of Multipurpose terminal;
- 2016: no dredging of maneuver basin or Adjacent areas of Multipurpose terminal.

The average volume dredged in River Mouth and Outer Basin each year is: 170,000 m³ and in maneuver basin and Adjacent Areas of Multipurpose Terminal was, excluding the year when no dredging was carried out, 170,000 m³.

These two volumes, making together 340,000 m³ plus the sand accumulated in the updrift breakwater each year, approximately 500,000 m³, make 840,000 m³ of sand to be dredged each year through a suction dredger and placed downdrift through a pipeline system.

Calculations were carried out considering a suction dredger like it was done for Aveiro Port situation.

6.2.5.1. Construction Cost Analysis

The cost of the suction dredger, provided by “José Ruas, Shipbulding” costs 1.5 million Euros and the construction of the weir jetty would be around 480,000 €.

Due to the distance between Multipurpose Terminal and sand placement area, a booster station would be required: 43,000 €.

\[ \text{TOTAL COST} = 2,023,000 \text{ €} \]

6.2.5.2. Operation Cost Analysis

Considering a work shift of 8 hours, a sand pumping rate of 750 m³/hour and a daily sand pumping rate of 6,000 m³ the required days to bypass 840,000 m³ of sand would be:

\[ \text{Number of days of dredging operations} = \frac{840,000}{6,000} = 140 \text{ days} \]

Given the fact that dredging operations would be carried out 20 days per month:

\[ \text{Number of months of dredging operations} = \frac{140}{20} = 7 \text{ months} \]

The biggest problem of this system is the 1,500 km distance between Multipurpose Terminal and sand placement area, in downdrift beaches. This situation would require not only a booster station (or more than one) but would also cause a big constraint to normal port operations.

Figure 6.26 represents a schematic view of how it would be a system like this in Figueira da Foz Port. Due to the huge length of pipeline that would have to be buried, the cost of these operations would impede the success of a system like this.
Even though, imagining a system with three times the length of the Pipeline system in Aveiro and, consequently, three times the energy consumption. This would happen both due to the booster fuel consumption and higher cost of maintenance and repairs.

Instead of 300 L/hour of operation, like in Aveiro Port case, calculations were done considering three times the consumption.

\[
\text{Cost} = \frac{900 \times 0.8}{750} = 0.96 \frac{\text{€}}{\text{m}^3}
\]

The cost per cubic meter of sand bypassed is still very low. However, the logistics that it would imply and the constraints to Port operations completely rule this method out of option.

6.2.6. JETTY HOUSING JET PUMPS, PUMP STATION CONNECTED TO A CLEAR WATER INTAKE AND PIPELINE SYSTEM WITH MULTIPLE DISCHARGE LOCATIONS

The method used for jetty design in Figueira da Foz Port updrift beach was exactly the same as Aveiro. The only thing that changes is the beach profile, as shown in Figure 6.27.

Even though some differences can be noted between Aveiro and Figueira da Foz updrift beaches’ profiles, any structural design variable would change. Admitting sand properties as the ones admitted for Aveiro Port calculations.

Calculations were developed just like they were for Aveiro Port situation.
6.2.6.1. Construction Cost Analysis

A comparison between Port of Ngqura and Figueira da Foz Port were developed, detailed in Table 6.9. Due to the less dynamic environment that is the depth of closure line in Figueira da Foz updrift beach, which has any relevant changes in the last years, the length of the pier can be considered shorter than in Aveiro.

Table 6.9 – Comparison between Figueira da Foz and Port of Ngqura Bypass features

<table>
<thead>
<tr>
<th></th>
<th>Ngqura</th>
<th>Aveiro</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jetty Length (m)</td>
<td>225</td>
<td>400</td>
</tr>
<tr>
<td>Piles Diameter (mm)</td>
<td>760</td>
<td>1,000</td>
</tr>
<tr>
<td>Deck elevation (m CD)</td>
<td>+ 8 m</td>
<td>+ 9 m</td>
</tr>
<tr>
<td>Pipeline System (m)</td>
<td>3,800</td>
<td>2,500</td>
</tr>
<tr>
<td>No. of Jet pumps</td>
<td>6</td>
<td>10</td>
</tr>
<tr>
<td>Maximum Volume to Bypass (m$^3$/year)</td>
<td>320,000</td>
<td>500,000</td>
</tr>
</tbody>
</table>

Taking into account the differences between the two systems:

- The required length of the jetty of Figueira is more or less twice of Ngqura;
- Due to environment characteristics, the Diameter of the piles must be 1,000 mm instead of 760 mm;
- Higher deck elevation due to the possible wave height to hit the structure;
- Shorter length of the pipeline system, but in Figueira da Foz Port case, there are at least 150 m of the pipeline which is buried in the navigation channel;
- Higher number of jet pumps, considering the highest volume to bypass each year.

Table 6.10 contains cost differences that the modifications between Figueira da Foz and Ngqura Sand Bypass System would cause, based on Table 6.11.
Table 6.10 – Cost comparison between sand bypass operation in Figueira da Foz and Ngqura Ports

<table>
<thead>
<tr>
<th></th>
<th>Jetty</th>
<th>Pipeline System (m)</th>
<th>No. of jet pumps</th>
<th>Pump system</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Length (m)</td>
<td>Diameter of the piles (mm)</td>
<td>Deck elevation (m CD)</td>
<td>Volume to Bypass (m³)</td>
</tr>
<tr>
<td>Ngqura</td>
<td>225</td>
<td>760</td>
<td>8</td>
<td>3,800</td>
</tr>
<tr>
<td>Cost (€)</td>
<td>1,900,000</td>
<td>900,000</td>
<td>415,000</td>
<td>45,000</td>
</tr>
<tr>
<td>Aveiro</td>
<td>400</td>
<td>1,000</td>
<td>9</td>
<td>2,000</td>
</tr>
<tr>
<td>Cost (€)</td>
<td>3,500,000</td>
<td>1,200,000</td>
<td>700,000</td>
<td>70,000</td>
</tr>
</tbody>
</table>

Difference of costs 2,200,000 €

Considering the difference of cost as 2 Million €, the total cost for a fixed sand bypass system in Figueira da Foz Port, with the objective to bypass 500,000 m³/year with a jetty 400 m long would be, approximately, 8.4 million € (total cost of Ngqura sand bypass system: 6,200,000 + 2,200,000 €).

6.2.6.2. Operation Cost Analysis

Like in Aveiro Port calculations, Tweed and Nerang River sand bypass systems and its corresponding operation costs were used to define the possible operation cost of a sand bypass system in Figueira da Foz Port.

Table 6.11 contains the most important differences between Figueira da Foz River Mouth and Nerang and Tweed River entrances.

Table 6.11 – Comparison between Australian Cases and Aveiro Port operational sand bypass cost

<table>
<thead>
<tr>
<th></th>
<th>Sand Bypass Volume (m³/year)</th>
<th>Length of the pipeline system (m)</th>
<th>Length of the jetty (m)</th>
<th>No. Of Jet Pumps</th>
<th>Cost per cubic meter (€/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nerang River</td>
<td>500,000</td>
<td>1,400</td>
<td>500</td>
<td>10</td>
<td>0.85</td>
</tr>
<tr>
<td>Tweed River</td>
<td>500,000</td>
<td>7,100</td>
<td>450</td>
<td>10</td>
<td>6.18</td>
</tr>
<tr>
<td>Fig. da Foz Port</td>
<td>500,000</td>
<td>2,000</td>
<td>400</td>
<td>10</td>
<td>???</td>
</tr>
</tbody>
</table>

The same calculations developed for Aveiro Port sand bypass system were also developed to Figueira da Foz. The cost per cubic meter of sand bypassed is explained as follows.

Figure 6.28 represents the scheme of a jetty fixed sand bypass system in Figueira da Foz Port.
Using some simple calculations, the cost per cubic meter bypassed in Figueira da Foz Port Sand Bypass System would be:

\[
\begin{align*}
7,100 - 1,400 &= 5,700 \text{ m} \\
6.18 - 0.85 &= 5.33 \text{ €} \\
7,100 - 2,000 &= 5,100 \text{ m}
\end{align*}
\]

That said, the cost per cubic meter of sand to bypass in Figueira da Foz Port sand bypass System would be:

\[
\text{Cost per cubic meter} = 6.18 - \frac{5,100 \times 5.33}{5,700} = 1.41 \text{ €/m}^3
\]
6.3. Feasibility Study of the Various Possible Solutions for each Port

From the calculations developed in chapter 5.3 resulted Tables 6.13 and 6.14, which contain a resume of cost of operation, construction and advantages, disadvantages of each possibility of sand bypass system in Aveiro and Figueira da Foz Ports.

The legend is as follows:

1. Crane Mounted Jet Pump in the Updrift Beach;
2. Jetty Housing Jet Pumps, Pump Station Connected to a Clear Water Intake and Pipeline System with Multiple Discharge Locations;
3. Weir Jetty and Sand Placement Through Rainbow Technique;
5. Weir Jetty and Sand Placement Downdrift Through Floating/buried Pipeline System;

Table 6.12 and Table 6.13 contain a summary of all the studied sand bypass systems and respective advantages/disadvantages. They contain an analysis both for Aveiro and Figueira da Foz Ports, since most of the systems cause the same kind of constraints for the two ports.
### Table 6.12 - Advantages, Disadvantages, and Costs for Construction and Operation of 6 Types of Sand Bypass Systems, Aveiro Port

<table>
<thead>
<tr>
<th>Costs</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Advantages</strong></td>
<td>- Easy change of source area allows both reduction of trapping by debris and lack of sand problems.</td>
<td>- Existence of several jet pumps allow the sand trapping of a huge area.</td>
<td>- Relatively low operation costs comparing with any other dredging method with sand placement directly in the beach.</td>
<td>- Accommodation of huge volumes of sand in the hopper structure to subsequent discharge.</td>
<td>- Extremely low operation costs.</td>
<td>- Sand placement in extremely accurate areas.</td>
</tr>
<tr>
<td><strong>Disadvantages</strong></td>
<td>- A unique jet pump is not enough for the Portuguese scenario.</td>
<td>- Tendency to blockage of jet pumps by debris since they are not movable.</td>
<td>- Significant wear of jet pumps due to salt water and marine life action.</td>
<td>- The distance from the hopper structure to the sand placement area is enormous and its associated costs are high.</td>
<td>- Constraints to normal operation of the Port due to location of the dredger in the navigation channel.</td>
<td>- High maintenance costs.</td>
</tr>
<tr>
<td>Construction Cost (€)</td>
<td>4,712,000</td>
<td>9,200,000</td>
<td>480,000 (for the weir jetty)</td>
<td>3,073,000</td>
<td>2,023,000</td>
<td>480,000 (for the weir jetty)</td>
</tr>
<tr>
<td>Operation Cost (€/m³)</td>
<td>15</td>
<td>2.35</td>
<td>5</td>
<td>10</td>
<td>0.32</td>
<td>5</td>
</tr>
</tbody>
</table>
## Table 6.13 - Advantages, Disadvantages and Costs for Construction and Operation of 6 Types of Sand Bypass Systems, Figueira da Foz Port

<table>
<thead>
<tr>
<th>Possible Alternatives</th>
<th>Fixed Systems</th>
<th>Semimobile Systems</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Advantages</strong></td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>- Easy change of</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>source area allows</td>
<td>5</td>
<td>6</td>
</tr>
<tr>
<td>both reduction of</td>
<td></td>
<td></td>
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<tr>
<td>trapping by debris</td>
<td></td>
<td></td>
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<tr>
<td>and lack of sand</td>
<td></td>
<td></td>
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<tr>
<td>problems.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Existence of several</td>
<td></td>
<td></td>
</tr>
<tr>
<td>jet pumps allow the</td>
<td></td>
<td></td>
</tr>
<tr>
<td>sand trapping of a</td>
<td></td>
<td></td>
</tr>
<tr>
<td>huge area.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Technology known to</td>
<td></td>
<td></td>
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<tr>
<td>work with such big</td>
<td></td>
<td></td>
</tr>
<tr>
<td>volumes in other</td>
<td></td>
<td></td>
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<tr>
<td>countries.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Relatively low</td>
<td></td>
<td></td>
</tr>
<tr>
<td>operation costs</td>
<td></td>
<td></td>
</tr>
<tr>
<td>comparing with any</td>
<td></td>
<td></td>
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<tr>
<td>other dredging</td>
<td></td>
<td></td>
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<tr>
<td>method with sand</td>
<td></td>
<td></td>
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<tr>
<td>placement directly in</td>
<td></td>
<td></td>
</tr>
<tr>
<td>the beach.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Accommodation of</td>
<td></td>
<td></td>
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<tr>
<td>huge volumes of sand</td>
<td></td>
<td></td>
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<tr>
<td>in the hopper</td>
<td></td>
<td></td>
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<tr>
<td>structure to</td>
<td></td>
<td></td>
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<tr>
<td>subsequent</td>
<td></td>
<td></td>
</tr>
<tr>
<td>discharge.</td>
<td></td>
<td></td>
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<tr>
<td>- Extremely low</td>
<td></td>
<td></td>
</tr>
<tr>
<td>operation costs.</td>
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| Construction Cost (£) | 4,612,000 | 8,400,000 | 480,000 for the weir jetty | 3,030,000 | 2,023,000 | 480,000 for the weir jetty |
| Operation Cost (£/m³) | 15 | 1.41 | 5 | 3.6 | 0.96 | 5 |
6.3.1. CRANE MOUNTED JET PUMP IN THE UPDRIFT BEACH

This kind of bypass systems and the ones used in Lake and South Lake Worth Inlets are very useful and recommended when the target of bypassing volume per year is less or equal to 100,000 m$^3$ per year. This is the maximum volume that a single jet pump, due to its restrictions in maximum diameter and its extremely expensive cost, can bypass during one year. More than that value requires a second or third, or even a fourth jet pump which already implies a robust and fixed structure to hold all those jet pumps.

That said, this kind of system is not a valid alternative due to the target bypassing volume per year required in the Portuguese coastline.

6.3.2. JETTY HOUSING JET PUMPS, PUMP STATION CONNECTED TO A CLEAR WATER INTAKE AND PIPELINE SYSTEM WITH MULTIPLE DISCHARGE LOCATIONS

Due to its dimension and capacity to easily bypass the required volume for Portuguese cases, this is the most viable one, both from an economically and functional point of view. Another great advantage is the proven effectiveness that a system like this has been getting all over the world. There are systems like these in 3 completely different countries in the world: Australia, Japan and South Africa. These same countries have different wave regimes, the volume to bypass is not the same and the environment where they are, is also different (an inlet in Australia, a Deep Water Port in South Africa and a normal harbour in Japan). Even though, solutions were arranged, designing was carried out and this sand bypass solution gets more and more hype around the world every year. The biggest doubt about the operation of a system like this in the Portuguese coastline are the operational and maintenance costs. The wave regime must cause bigger damages to the structure, which must be predicted and accurately calculated in advance.

6.3.3. WEIR JETTY AND SAND PLACEMENT THROUGH RAINBOW TECHNIQUE

This is a possible solution for Aveiro and Figueira da Foz Ports. Apart from the strong visual impact that it causes, effects are known as excellent around the world. But, as it is very effective when it is working, if a severe winter happens, due to fact that the system is operated by a hopper dredger, the dredger cannot leave the shelter area of the port. If the dredger cannot leave the port, dredging is not carried out and the sand accumulation area, an area which is caused by the weir jetty, will invade the navigation channel and cause navigational constraints which could affect the operability of the port. Sand placement by rainbow technique is not a good system to permanent beach nourishment since it is a very sensitive system regarding wave conditions.

The problem of the weir jetty and the subsequent possible siltation of the navigation channel could be resolved with a rocky structure. This rocky structure would have a huge capacity to sand accumulation and the navigation channel would not suffer from siltation like in the case of the weir jetty. The problem of this system is the space it occupies in the channel. The future developments of Portuguese ports expect the entry of bigger ships in their areas and that is only possible if the navigation channel keeps fully operational and free of obstacles.
6.3.4. Weir Jetty and Sand Placement in Hopper System to Later Discharge Through Pipeline System

The problem created by the weir jetty remains but, in places like Figueira da Foz Port, where there are available and free berths where the hopper structure could be built, a system like these could work. However, a hopper dredger would be necessary anyway and the restraints caused by the wave regime, which can deprive the hopper to normal operate remain. This is a problem that will always exist and that can only be circumvented if operation occurs during summer. During summer, there are environmental restraints which, unless it is an emergency operation, do not allow dredging operations to be carried out. It all concludes that only a fixed bypass system can fulfill Portuguese coastline necessities and its constraints.

6.3.5. Weir Jetty and Sand Placement Downdrift Through Floating/Buried Pipeline System

This mixture between buried and floating pipeline systems is a good way of beach nourishment when dealing with small amounts of sand or when a lagoon has to be desilting. But if a permanent sand bypass solution is required, a most intrusive method must be used. This floating/buried solution would create so many constraints to the navigation channel, causing such a big loss of profit to the port authority that, even if it is a great solution for beach nourishment and erosion mitigation, it would never be accepted.

6.3.6. Weir Jetty and Sand Placement Downdrift Through Floating Pipeline System

Floating pipeline system is a very efficient way to bypass sand when dealing with free spaces. It is a good system to beach nourishment from offshore sources and when the wave height is relatively small. Due to the incapacity of a hopper dredger to navigate in stormy conditions, it would have to carried out during summer and the visual impact is also enormous if bathing season has already started (like what was done in Costa da Caparica which caused many complaints from different entities). Beach nourishment through floating pipeline would work as a preparation measure for bathing season and carried out after March, when the winter wave season had already finished. Anyway, it would never work as a permanent sand bypass system, and when dealing with such huge volumes of sand like in Aveiro and Figueira da Foz Ports situation, a fixed system is mandatory.
7

CONCLUSIONS AND FUTURE DEVELOPMENTS

7.1. CONCLUSIONS

The construction of both Aveiro and Figueira da Foz Port completely changed the dynamics of the Portuguese coastline with an influence in more than 100 km of it.

Even though there was a feasibility study for a sand bypass system in Aveiro Port back in 1960s, a permanent solution was never taken. Emergency and maintenance dredging operations are carried out every year since 1960s decade and dredging with direct placement in the beach were only carried out after breakwater’s extension or any maritime work in the Lagoon Mouth, due to the proven environmental impact it would cause in the downdrift beaches.

In Figueira da Foz Port and its adjacent areas, the same thing happens, with the additional advantage that an endangered Hospital is located downdrift of the port which requires extra care and more emergency actions. Almost permanent dredging operations are carried out in that Port, mainly due to the fact that it was never deepened until the point that Aveiro Port was, reason that is currently being studied by University of Aveiro. Siltation of Figueira da Foz River Mouth is very common which already caused some disasters and shipwrecks, what makes the deepening operation of the navigation channel even more important. Most of the sand which enters in the River Mouth and subsequently in the Navigation Channel comes from the longshore sediment transport. It was proven that the sediment transport of Mondego River, the one which ends in Figueira da Foz River mouth, is only responsible to transport up to 80,000 m$^3$ per year which is nothing compared to the necessary volume which is dredging every year since 2010.

Most of the sand inside Port areas comes from the longshore sediment transport of the Portuguese coastline and this is why the implementation of a permanent solution of sand bypassing has become even more urgent.

The analysis of dredging operations, in both Aveiro and Figueira da Foz Ports, in the last 7 years, was very conclusive and has proved that its costs are extremely competitive against the possible costs of a fixed sand bypass system. This also proved that if a sand bypass system is to be implemented, it has to be a very efficient one with approximately the same low prices as dredging operations, even though the sand placement area of those dredging operations is not the same as the sand bypass system would be.

In terms of already existing sand bypass systems around the world, the literature review effectively proved the existence of more than 5 dozens of relevant systems in the world, all over 5 continents. It
was also used to notice that, if a huge volume of sand has to be bypassed each year in a River Mouth, across two breakwaters, a fixed sand bypassing system is usually required. Such big volumes like the 400,000 m$^3$ in Aveiro Port and 500,000 m$^3$ Figueira da Foz Port, which are proven to be accumulating in the downdrift breakwater of these ports every year, are easily bypassed if an automatic and remotely controlled system is used.

That said, was developed not only a full analysis of 5 of those kind of systems but also its implementation and operational costs for the two case studies.

It comes to the conclusion that, effectively, if such a huge volume of sand has to be bypassed each year in a place like Aveiro or Figueira da Foz Ports adjacent areas, a fixed and robust sand bypass system must be built.

### 7.2. Future Developments

The analysis of dredging records in Aveiro and Figueira da Foz Ports must be a huge help for a realistic feasibility study of the implementation of a fixed sand bypass system in these ports. Costs per cubic meter, dredged volumes and months of operation must be used for purposes of determining the necessities of dredging in these ports and how a fixed sand bypass system could replace or complement it.

Considering beach profile’s evolution study, advancement/retreat of the coastline and accumulated volumes in updrift beaches of each port, it must and should be used for future studies regarding academic or more realistic works. It was determined using accurate and recent data provided by Aveiro and Figueira da Foz Port Authority, which have been developing this permanent control of the adjacent coastline of each port regarding the Environmental Impact Study carried out and implemented during the extension works of northern, and updrift, breakwater of each port.

The literature review and corresponding analysis of 5 analogous cases to the possible Portuguese cases of sand bypass systems, were mostly developed based on the last literature review available, from 1997. It was also carried out a strictly cross checking of information available on the web, required via e-mail or telephone to dozens of civil engineers around the world responsible for the most diverse sand bypass systems operating at the moment. It is important to clarify that the last full detailed literature review which were developed about sand bypass systems, were done regarding the implementation of the sand bypass system of Tweed River Entrance. It also consisted of detailing as much sand bypass systems as possible and subsequently, even more detailed reviews of the most similar analogous systems were carried out. Even more important was the fact that, 3 years after the publishing of this review, the construction of the, nowadays, most successful case of sand bypassing in the world, was carried out.

Even being a good indicative cost, as an immediate future, the preliminary design of the jetty structure and corresponding pipeline’s and pump’s systems must be finished and developed in order to strictly define the exact cost that the implementation of a fixed sand bypass system in Portugal would impose. An accurately study of the sand characteristics also has to be carried out to properly define the environment where the jetty has to be built.

Numerical modelling must also be developed and continually improved to better simulate the beach dynamics around Aveiro and Figueira da Foz Ports. A sand bypass system regarding half a million cubic meters of sand every year will influence a huge strip of the Portuguese coastline which has to be accurately determined.
Meetings with affected Port Authorities, Ministry of Environment and population are also very important and the immediate next step to take.
REFERENCES


Ware, D. *Tweed River Entrance Sand Bypass Project. Case Study for CoastAdapt.* California, 1957.


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https://www.transnetnationalportsauthority.net/Pages/default.aspx

APPENDIXES
APPENDIX 1

WAVE DATA IN ANALOGOUS CASES BETWEEN 2011 AND 2016
Fig. 1 – Aveiro/Figueira da Foz Wave Records, 2011

Fig. 2 – Ngqura Wave Records, 2011
Fig. 3 – Durban Wave Records, 2011

Fig. 4 – Indian River Wave Records, 2011
Sand Bypass Study, Aveiro Lagoon Mouth and Figueira da Foz River Mouth Case Studies

Fig. 5 – Tweed/Nerang River Wave Records, 2011

Fig. 6 – Aveiro/Figueira da Foz Wave Records, 2012
Fig. 7 – Ngqura Wave Records, 2012

Fig. 8 – Durban Wave Records, 2012
Fig. 9 – Indian River Wave Records, 2012

Fig. 10 – Tweed/Nerang River Wave Records, 2012
Fig. 13 – Durban Wave Records, 2013

Fig. 14 – Indian River Wave Records, 2013
Tweed/Nerang River - 2013

Fig. 15 – Tweed/Nerang River Wave Records, 2013

Aveiro/Figueira da Foz (Leixões Buoy) - 2014

Fig. 16 – Aveiro/Figueira da Foz Wave Records, 2014
Fig. 17 – Ngqura Wave Records, 2014

Fig. 18 – Durban Wave Records, 2014
Fig. 19 – Indian River Wave Records, 2014

Fig. 20 – Tweed/Nerang River Wave Records, 2014
Fig. 21 – Aveiro/Figueira da Foz Wave Records, 2015

Fig. 22 – Ngqura Wave Records, 2015
Sand Bypass Study. Aveiro Lagoon Mouth and Figueira da Foz River Mouth Case Studies

Fig. 23 – Durban Wave Records, 2015

Fig. 24 – Indian River Wave Records, 2015
Fig. 25 – Tweed/Nerang River Wave Records, 2015

Fig. 26 – Aveiro/Figueira da Foz Wave Records, 2016
Fig. 27 – Ngqura Wave Records, 2016

Fig. 28 – Durban Wave Records, 2016
Sand Bypass Study: Aveiro Lagoon Mouth and Figueira da Foz River Mouth Case Studies

**Indian River - 2016**

Fig. 29 – Indian River Wave Records, 2016

**Tweed/Nerang River - 2016**

Fig. 30 – Tweed/Nerang River Wave Records, 2016
APPENDIX 2

Beach Profile Evolution, Aveiro Coastline
Fig. 31 – Location of Beach Profiles, Aveiro Coastline

* DC = Depth of Closure
Fig. 36 – P5

Fig. 37 – P6
Sand Bypass Study. Aveiro Lagoon Mouth and Figueira da Foz River Mouth Case Studies

Fig. 40 – P9

Fig. 41 – P10
APPENDIX 3

Photographic report of Aveiro and Figueira da Foz Beach Profile’s Location
Sand Bypass Study. Aveiro Lagoon Mouth and Figueira da Foz River Mouth Case Studies

Fig. 48 – P5

Fig. 49 – P6
APPENDIX 4

Beach Profile Evolution, Figueira da Foz Coastline
Fig. 56 – Location of Beach Profiles, Figueira da Foz Coastline
Profile 9

Fig. 65 – P9

Profile 10

Fig. 66 – P10
Sand Bypass Study. Aveiro Lagoon Mouth and Figueira da Foz River Mouth Case Studies

Fig. 69 – P13

Fig. 70 – P14
APPENDIX 5

Hmax comparison between the 5 international analogous cases
Fig. 72 – Hmax Records, 2010-2016 in Sand Bypass Analogous Cases