

Environmental & Engineering Geoscience

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Key Terms: *Coastal Dynamics, Hydraulic Structures, Geomaterials, Coastal Geoengineering, GIS*

INTRODUCTION

ABSTRACT

Shoreline change in the Espinho area (northwest Portugal) is a chronic problem. The present study takes advantage of geographical information system (GIS) tools to contribute to the knowledge of the geologic and geomorphological dynamics of the Espinho shoreline. A GIS-based monitoring project was compiled, which gathers information on all coastal works located along the Espinho shoreline, focusing especially on construction, monitoring, and repair aspects. Shoreline change was analyzed using the ArcGIS extension “Digital Shoreline Analysis System” (DSAS) to understand this important aspect of coastal management. This work also emphasizes the importance of geotechnical assessment of coastal protection structures in diagnosing their degree of damage and/or deterioration so that one can plan more efficient maintenance works. Our results indicate a general trend of erosion to the south and accretion to the north of the Espinho coastal area. Geoengineering characterization of the Paramos groin defines three main zones for the armor block materials (i.e., Zones I, II/III, and IV), which show, respectively, very low, medium to high, and low deterioration levels.

Coastal areas represent a dynamic environment of vital importance to human society. Over 40 percent of human settlements are located near the coast—a proportion that is still increasing (Carter, 1988). The sustainable management of coastal areas depends on gathering proper knowledge and understanding of the coastal development and combining it with relevant information to develop effective tools with which to aid the decision-making process. Coastal zone management and coastal defense are central fields of interest all over the world, and effective management of coastal zone dynamics is a key issue of research (Taveira Pinto, 2003; MAOTDR, 2008). Carter (1988) subdivides coastal management into the three broad areas of policy, planning, and practice. Most coastal management issues, he suggests, “raise conflict between various coastal user and interest groups.” These conflicts may include disputes between jurisdictions over access to key resources, conflicts between sectors of society about the allocation of these resources, conflicts between human use of the coast and the ecological requirements of other components of the coastal system, and conflicts arising through misunderstanding or underestimating the operational requirements of natural coastal processes such as sediment movement, shoreline erosion, etc. Nowadays, in recognition of the many problems that have arisen in the past through inappropriate use and management of the coast, a

new, more “environmentally oriented” ethos of coastal management is emerging, one that is based on more holistic, transdisciplinary, and integrative principles and that aims at sustainable management of coastal resources. This new philosophy depends, however, on a thorough understanding of the entities and relationships at work in the coastal system, which in turn demands a solid base of data and information to be harnessed in support of decision making. Thus, for these and many other reasons, coastal scientists, engineers, and administrators are increasingly looking for new developments in information technology, tools, and methodologies that might assist them in their work (Carter, 1988; McCleese, 2000).

One crucial part of any successful coastal maintenance program is its monitoring (McCleese, 2000). The complexity and scope of a monitoring effort can vary widely, from simple periodic on-site visual inspections at the low end of the scale to elaborate and expensive long-term measurement programs at the other extreme. The most important aspect of any monitoring and inspection program is the careful determination of the purpose of this issue. Without a clear definition of the monitoring goals, resources and instruments will not be used in the most beneficial manner, and it is likely that the information gathered will be insufficient to accurately evaluate the project and to recommend appropriate maintenance programs.

One of the most important aspects of coastal management and planning programs that requires further investigation is shoreline dynamics. This term includes not only the progression and erosion of coastlines, but also protection against erosion. The latter is a complex problem, for which different methods and coastal structures may be used to protect the shoreline, according to the specific framework. Groins are among the most common structures built for erosion control. These are transverse coastal structures, the function of which is to intersect the waves to minimize their erosive power; they are also designed to regulate littoral sediment transport in order to stabilize the beach (Gomes, 1977; USACE, 2002). Normally groins are built in groups designated as groin fields. These coastal defense works may be integrated with longitudinal constructions, and in some cases they may be artificially nourished (LCPC, 1989; CIRIA/CUR, 1991; USACE, 1995; and CIRIA et al., 2007). As a result of their characteristics, these structures are designed under the assumption that maintenance and repair work will be needed during the life of the structure (USACE, 1990; Silva, 1996; and Santos et al., 2003). Geographical information systems (GIS) provide ideal platforms for acquiring coastal information and for analysis of this data with an eye

toward monitoring coastal zone progression and defense. GIS are highly suitable for analyzing geologic and geomorphological data, revealing trends and interrelationships that would be more difficult to discover in tabular format. Moreover, GIS allow policy makers to easily visualize problems in relation to coastal erosion and the condition of existing protection structures for effective resource utilization.

In Portugal, the coastal zone of Espinho is situated on the western Atlantic shoreline of the Iberian Peninsula. In this area, the erosion phenomena are usually intense and have been well known since the 19th century. To protect this part of the Portuguese shoreline several structures have been constructed—the majority during the past. In Portugal, several public institutions share the responsibility for coastal zone management, which sometimes gives rise to overlapping or ineffective actions (MAOTDR, 2008). Nevertheless, the prime legal authority can be identified as being the Ministry for Towns, Territorial Planning and Environment, especially through the Portuguese Water Institute (INAG) and the Institute for Nature Conservation and Biodiversity (ICNB). In fact, INAG and ICNB together have jurisdiction over all of the Portuguese coastal zones, except for the areas under harbor jurisdiction.

The main goal of this work was the application of GIS tools and concepts to the study of the Espinho coastal zone. This involved the creation of a GIS-based monitoring program to gather information on all coastal works located along the Espinho shoreline, focusing especially on construction, monitoring, and repairing aspects. A long-term estimation of the erosion and accretion rates in several different locations was then performed using GIS extension tools. This analysis allowed us to make predictions on future displacements of the Espinho shoreline. Finally, a geotechnical mapping evaluation of the rock blocks used in groins from the Espinho shoreline was carried out, based on lithology, weathering grade, and stiffness of the rock materials.

STUDY AREA

Espinho is a municipality in the Aveiro district, situated on the North Atlantic coast approximately 16 km south of Porto city, the second largest urban area in Portugal (Figure 1). The town of Espinho has a total area of 21.1 km² and a population of 33,701 inhabitants (census 2001; after PDM [2004]), including five parishes (Espinho, Anta, Guetim, Silvalde, and Paramos); about 20,000 of the inhabitants are concentrated in the urban seafront of Espinho (Veloso Gomes et al., 2002, 2006b; PDM, 2004).

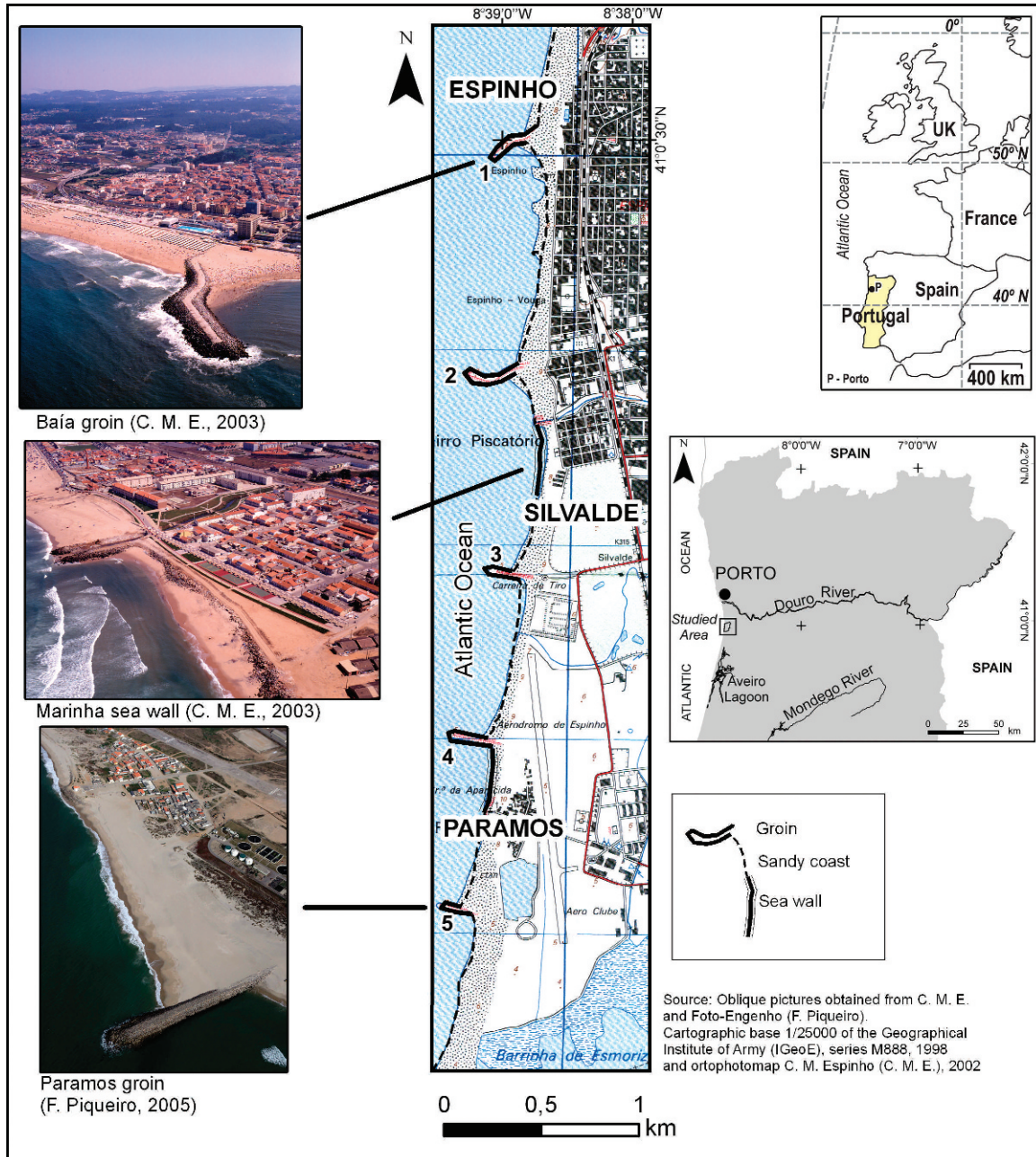


Figure 1. Espinho coastal study area.

Coastal erosion in Espinho has been popular news, recorded since 1869 (Lima, 1979, 1982), as evidenced by several historical documents (Figure 2). Indeed, the first reported erosion dates back to 1860 (Ortigão, 1876), and old maps show that the urban area of Espinho was much larger, extending further seaward to positions that have since been lost to the sea (Bandeira de Melo, 1870, 1900, in Lopes [1995]). The continuous retreat and advance of the Espinho shoreline several meters landward and seaward led to the construction of the first defenses, in 1909, but by 1911, these had been naturally destroyed. Since

then several protection structures have successively been put in place to protect the city (Perdigão, 1931; Mota Oliveira and Martins, 1991; Mota Oliveira et al., 2000; and Trigo Teixeira, 2003). Figure 2 illustrates not only the occurrence of some disastrous episodes of sea invasions in the Espinho region but also some evidence of the construction of protection works. This historical compilation of events demonstrates the importance of coastal research in the area.

Presently, two large groins, one in the north and another in the south, and two seawalls comprise the main structures protecting the seafront of Espinho,



Figure 2. Historical images of early 20th century from the Espinho shoreline (Espinho City Council Archives).

and the situation is considered to be stable. The main erosion problems persisting in the downdrift area are due to lack of sediment transport. The most vulnerable area in terms of erosion is the urban seafront of Paramos (Veloso Gomes et al., 2003), located in between Espinho and Esmoriz. The main problems identified in this narrow strip are due mostly to sandy coastal areas that have no natural rock protection, where continuous erosion results in destruction of almost all sand dunes (Dias et al., 2000). Table 1 summarizes the main characteristics of the groins from the Espinho region and the designations used for each coastal structure (see Figure 1), along with the types of different approaches studied.

Geological and Geomorphological Overview

The regional geology of the Espinho area is related to two different Iberian geotectonic domains: meta-sedimentary and crystalline bedrock, belonging to the Ossa-Morena Zone (Chaminé, 2000; Chaminé et al., 2003), and the northern part of the Lusitanian sedimentary cover, a tectonic basin developed like an aulacogen during Meso-Cenozoic times (Araújo et al., 2003; Gomes et al., 2006, 2007; and Gomes, 2008).

The shaping of coastal landforms has been influenced by a range of morphogenic factors. While some coastlines have changed little over the past 6,000 years, most have advanced or retreated, and some have shown alternations of advance and retreat (Bird,

Table 1. Summary of the main characteristics of groins in the Espinho region (compiled data from SOMAGUE [1980] and Veloso Gomes et al. [2002]).

Protection Structure Designation (present study)	ID*	Type of Coastal Structures	Location	Construction Date	Length (m)	Groins		
						Geotechnical Evaluation	Evaluation (SNIRLit, 2002)	DSAS Study
1	Structure 1/1	Groin	Espinho	1918/1981/1983	350	X	X	X
2	Structure 2/2	Groin	Espinho	1981/1983	400	X	X	X
—	—	Seawall	Espinho	—	400		X	
3	Structure 3/3	Groin	Espinho	1981/1983	300	X	X	X
4	Structure 4/4	Groin	Paramos	1981/1983	280		X	X
—	—	Seawall	Paramos	—	100		X	
5	—/5	Groin	Paramos	1985	280	X	X	X

DSAS = Digital Shoreline Analysis System.

*Identification (ID) according to SOMAGUE (1980)/Veloso Gomes et al. (2002).

1997). The Portuguese coast between the city of Espinho and Mondego cape is undergoing morphological changes (Dias et al., 2000). One of the most common characteristics of this littoral stretch is the so-called littoral platform (Araújo, 2002), encompassing different altitudes and bordered from the inland by a contrasting straight relief (Figure 3). The littoral platform ranges from 75 m in elevation (on the north, close to Ave River) to 130 m in elevation (at the south) and drops down toward the sea like a staircase (Brum Ferreira, 1983). This platform is bounded to the east by a step relief (i.e., the marginal relief) (Araújo, 1991) and is a regional fault scarp related to the Porto-Coimbra-Tomar shear zone (Chaminé, 2000; Gomes, 2008). This planation surface is generally covered with several outcrops of Plio-Pleistocene deposits (Teixeira et al., 1962). This platform has been considered a stable staircase of old marine deposits, indicative of the eustatic fluctuations. However, recent studies bring new insight that many of these deposits have a continental origin (Granja et al., 1999; Araújo, 2002).

MATERIALS AND METHODS

Three different cartographic sources were used for the study of the Espinho coastal zone: (i) the Pre-project Planning for the execution of the coastal protection structures in Espinho region presented by SOMAGUE (1980); (ii) the Espinho City Council cartographic base of 1993 (scale 1/5,000); and (iii) the 2002 orthophotomap of Espinho City Council. Two other additional sources of information were used to elaborate the GIS-based monitoring project: (a) the monitoring data available at SNIRLit—National Information System of Littoral Resources (SNIRLit, 2002)—and (b) the basic information on coastal works from the Espinho region previously compiled by Pires (2005, 2007) and Pires et al. (2006, 2007). The

latest records on the Espinho coastal zone available in SNIRLit date back to 2002. The information on the coastal works includes data related to the design features of the structures (e.g., location, cost, length) as well as their actual condition, eventual pathologies, and needed repairs. These information sources were georeferenced, and all the data were rectified before vectorization using more than 20 control points. The vectorization was used to represent beach areas, protection structures, and bathymetric information (0.0 and +5.0 m.s.l., mean sea level).

The study of the variation of the Espinho shoreline focused on the analysis of the coastal dynamics and the spatiotemporal changes of coastal morphology for the period between 1993 and 2002 and took advantage of the Digital Shoreline Analysis System (DSAS) extension. DSAS is the most user-friendly and powerful tool currently available for measuring the shoreline displacement. It was originally developed by Thieler and Danforth (1994) using loosely coupled programming techniques. The current versions use the ArcView Avenue Macro language, which converted the tool into an extension of ArcView 3.3. Within an ArcView environment, DSAS can benefit from other GIS capabilities of ArcView, such as importing of shapefiles, coverages, and grids, as well as editing and changing projections. The latest version of DSAS can be downloaded freely from the U.S. Geological Survey web page (Thieler et al., 2005). DSAS is an extension that enhances the normal functionality of ESRI ArcGIS software and enables users to calculate shoreline rate-of-change statistics from a time series of multiple shoreline positions. The extension was designed to aid in historic shoreline change analysis (Bailey and Gatrell, 1995). DSAS is also useful for data sets that use polylines as a representation of a feature's position at a specific point in time, such as the forward limit of a glacier; river channel boundaries, and land use and land cover maps. DSAS works by generating

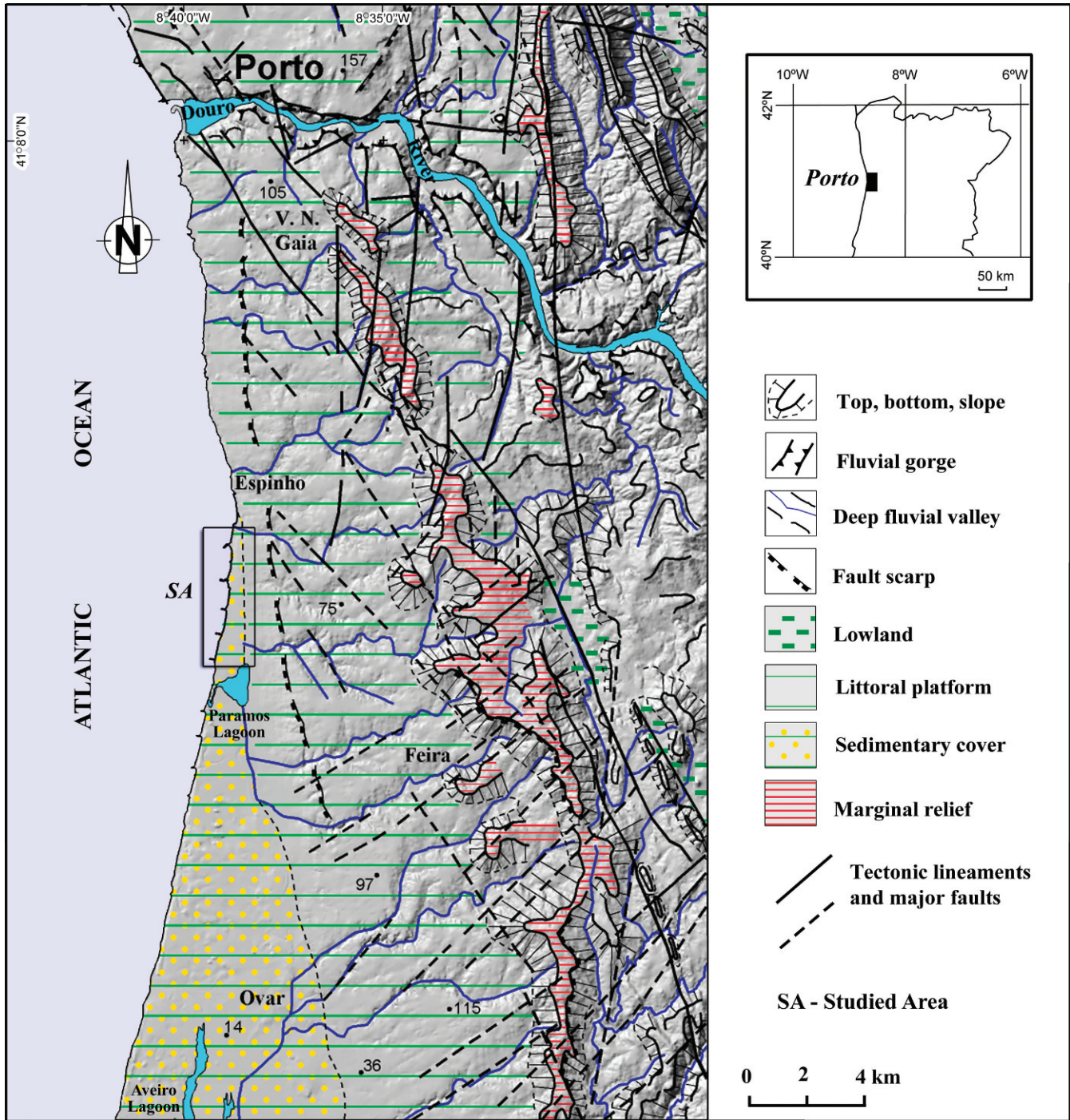


Figure 3. Geomorphological outline of Espinho region, South of Porto city, northwest Portugal (adapted from Gomes et al. [2006, 2007] and Gomes [2008]). Shaded image relief of the studied area, generated from digitization of elevation contour lines of the 1:25,000 scale. Ground resolution is 10 m.

orthogonal transects at a user-defined separation and then calculating rates of change and associated statistics that are reported in an attribute table. The DSAS tool requires user data to meet specific field requirements: (i) the baseline is the starting point for all transects and is therefore one of the most important

components of the shoreline change analysis process; (ii) the baseline must be contained in a single shapefile (and therefore is a single feature class once imported into the geo-database); and (iii) the user should take the time to manually edit and smooth the baseline depending upon the particular study area.

Several statistical methods are available to estimate annual erosion rates and to forecast shoreline positions, such as end point (EP), linear regression, time-series analysis, and geostatistics. The EP rate (EPR) was used in this work and was calculated by dividing the distance of shoreline movement by the time elapsed between the earliest and latest measurements (i.e., the oldest and the most recent shoreline). The major advantage of the EPR is its ease of computation and minimal requirement for shoreline data (two shorelines). The major disadvantage is that in cases in which more than two shorelines are available, the information about shoreline behavior provided by additional shorelines is neglected. Thus, changes in sign or magnitude of the shoreline movement trend or cyclicity of behavior may be missed. For the Espinho coastal area we determined eight zones representing different beach areas, and we also vectorized the lines to evaluate displacement of the head zone of the groins. The DSAS extension was then applied to assess the evolution of the shoreline according to the parameters indicated in Figure 4. The methodology applied in the present study combines several field techniques and various types of inputs/tools (Figure 4), establishing an interdisciplinary connection of geoenvironmental concepts and an analysis of coastal dynamics for the planning of maritime structures.

The geotechnical mapping evaluation of the groin of Paramos (Espinho shoreline) was performed according to a previously established methodology (Pires et al., 2006, 2009; Pires and Chaminé, 2007, 2009). This methodology is based on the recommendations and terminology of the *Manual of the Use of Rock in Coastal and Shoreline Engineering* from CIRIA/CUR (1991) and CIRIA et al. (2007) as well as on the proposal of geologic and geotechnical characterization of rock masses by ISRM (1978a,b, 1981) and the Geological Society Engineering Working Group (1995). A geotechnical datasheet was used for the recognition and visual evaluation of the rock material constituting the groin. A georeferenced GIS database for this structure was then set up using the data collected and aerial images of the area (Gonçalves and Piqueiro, 2004; Cunha et al., 2006; and Pires et al., 2009). A detailed mapping of the rock blocks constituting the structure was then prepared using the aerial photographic database. Afterwards, more than 5,000 block materials on the groin's superficial section (armor layer) were vectorized into a GIS base. Sampling along a scanline is an accurate method for the systematic collection of geological and/or geotechnical information (e.g., ISRM, 1981; Dinis da Gama, 1983, 1995; and CIRIA et al., 2007). Moreover, in several geologic-geotechnical situations

it is the easiest and fastest way to collect data. This approach allowed us to obtain thematic maps of the Paramos groin armor layer that were useful for evaluating various geotechnical parameters (ISRM, 1978b, 1981; Pires and Chaminé, 2007, 2009 [and references therein]). This assessment was also supplemented with walkover surveys carried out to record (with the aid of photographs and high-accuracy GIS data collection system Trimble Geoexplorer GPS) not only the overall condition of the structure, including any obvious rock movements, but also changes in the groin profile, type of lithology, etc.

These visual evaluations were supported by the use of the inspection datasheet, where the most important aspects and parameters were registered, including lithology, weathering grade, petrophysical characteristics, and geomechanical features of block materials (Fookes and Poole, 1981; Lienhart, 1998). For the evaluation of the uniaxial compressive strength of rocks and materials (concrete) in the groin, the Schmidt Hammer technique was used (e.g., Katz et al., 2000; Kahraman, 2001). This methodology was further refined through the application of GIS tools (e.g., Burke et al., 2001) and was used to create thematic geotechnical zoning maps of the block groins (e.g., Zuquette and Gandolfi, 2004; Pires et al., 2009).

RESULTS AND DISCUSSION

Within the scope of the present work, an interactive GIS-based monitoring project was created for the coastal zone of Espinho. This information system represents the actual condition of the Espinho shoreline as well as the state of degradation of the existing coastal protection structures (Figure 5). It includes a spatial representation of all groins and seawalls from Espinho, and it also stores all the relevant elements, specifications, and photos obtained during the process of information gathering. In brief, it assembles specific data on the following issues: (i) coastal protection structure identification; (ii) present condition of the coastal protection structures with hyperlinks to photos by *SNIRLit*; (iii) a geotechnical assessment of the coastal protection structures, including observed pathologies and indications on the eventual need of future repairs; and (iv) technical specifications, such as the kind of structures, type, location, year of construction, length, volume of blocks used in the construction, and costs. The information system developed in the GIS environment is useful for long-term accumulation of coastal data, while allowing for easy and accurate measurement and forecast of shoreline displacement.

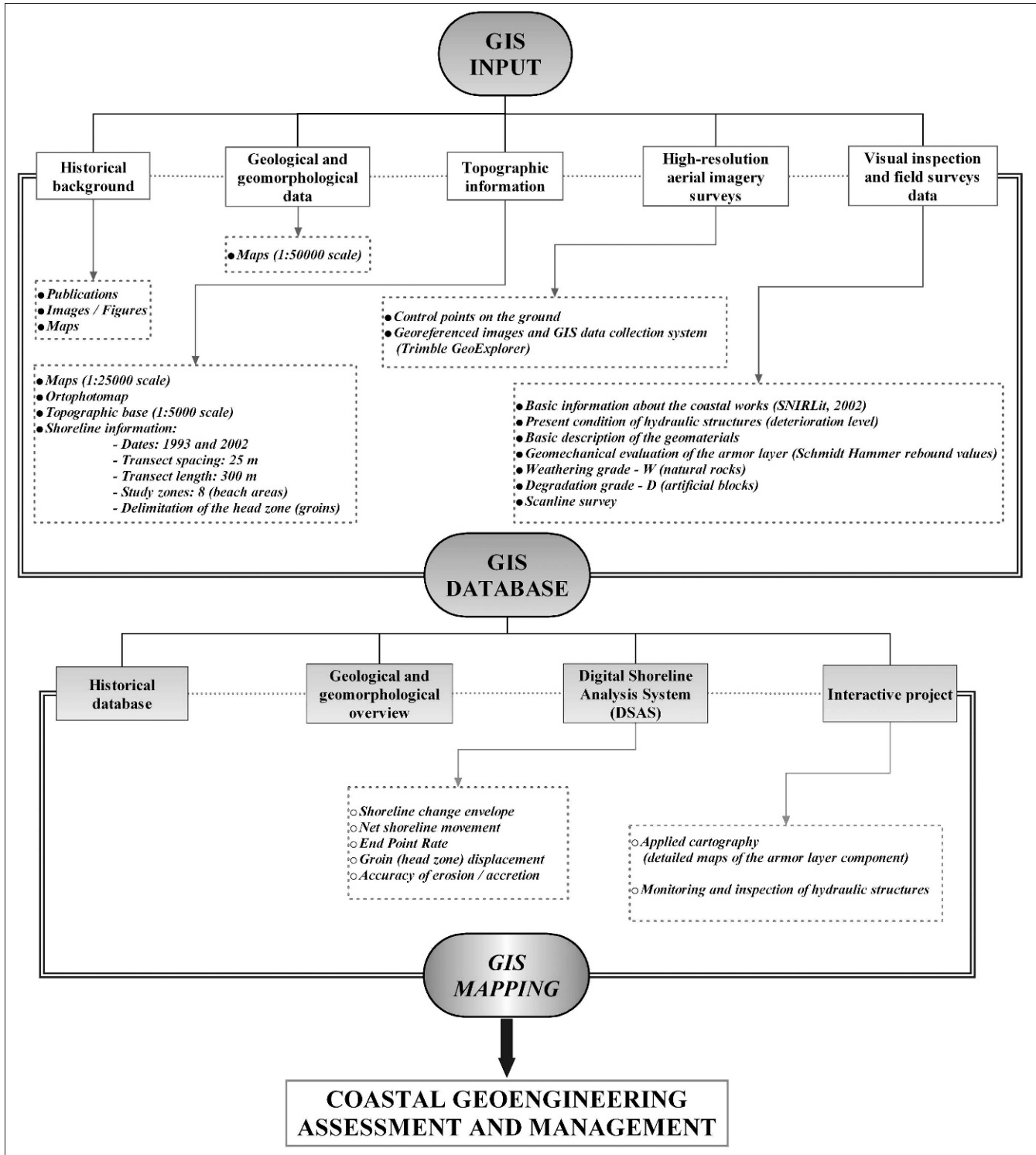


Figure 4. Conceptual flowchart for the dynamics of coastal geoengineering system assessment.

Estimation of the rates of erosion and accretion along the study area was performed for the 9-year period using the positions of the Espinho shoreline in 1993 and 2002. According to the results obtained, zone 4 (south of Marinha groin) shows a general

trend of erosion. In agreement with this, the main accretion area is located in the north (zones 1 to 3). Figure 6 represents the beach areas that were studied and the corresponding values of erosion or accretion, as determined by the transect methods employed by

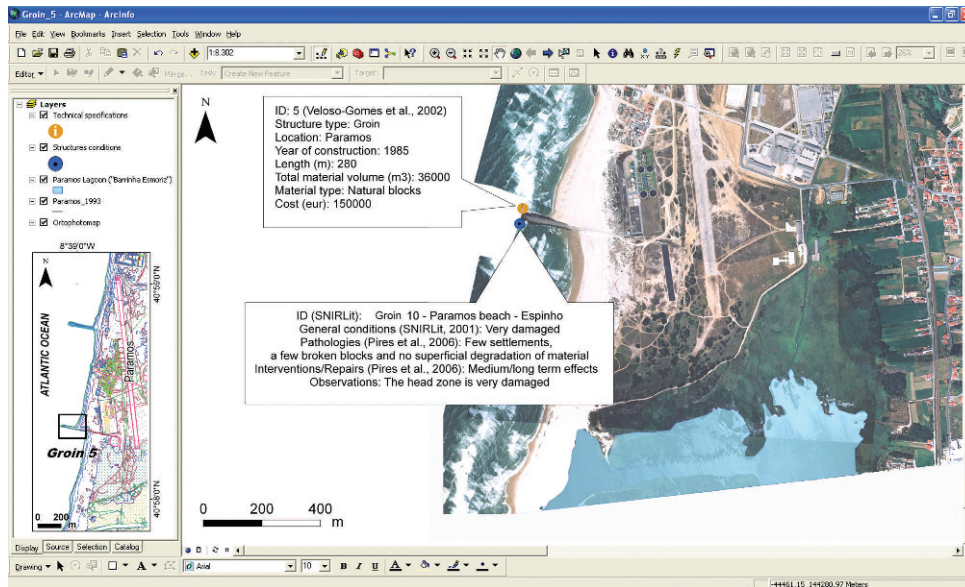


Figure 5. GIS database: an example of the type of information recorded for the Paramos groin (groin 5).

DSAS. The results indicate a general trend of erosion for the south of Espinho, with an average rate of 2.72 m/yr, whereas the mean rate of accretion estimated for the north of the study area is 3.21 m/yr. This figure shows very well the advance of the sea in the Paramos region (south of Espinho), which is one of the most affected sectors. These results are in agreement with those estimated by Dias et al. (1994) and Dias (2005) using other methodologies and for different temporal periods. These authors report a mean erosion rate of 3.8 m/yr for the period between 1870 and 1954, a value close to that obtained in the present work for a temporal interval of just 9 years. We also estimated the areas of land loss or gain for each zone (Figure 7a). This estimation was based on polygon vectorization for each section, with subsequent determination of the area of the polygons (Moran, 2003).

Within the Espinho coastal zone, the area of accretion has been estimated at about 60,000 m²/yr (Figure 7b), corresponding to 56 percent of the total affected area. These results are in agreement with those reported by other authors (e.g., Dias et al., 1994; Veloso Gomes et al., 2006a; and MAOTDR, 2008), who concluded that although the measures implemented in the Espinho area efficiently protect the northern part of the coast, they are ineffective in protecting its southern part. The displacement/settlement of blocks for the head zone of the groins is exemplified for groin 2, which shows movement or the destruction of this zone in the period ranging from 1993 and 2002 (Figure 8). Of the five groins studied, only groin 1 did not present visible settlements. Groin 4 underwent maximum change, with about 1,800 m² of settlement

during the study period, and groin 5 had the lowest change, at 233 m². Groins 2 and 3 present values showing approximately 900 m² of displacement.

The use of the method of transects from DSAS extension offered a flexible way to analyze Espinho coastal dynamics. Although based on just two shorelines and a short elapsed time, the method employed by the DSAS extension was powerful enough to confirm the marked evolution of the coastline during this period, clearly indicating the areas showing considerable erosion and accretion changes. Furthermore, ArcGIS embedded functions were instrumental in estimating (i) the total area affected by coastal advance and retreat and (ii) the annual average erosion and accretion rates.

Geotechnical mapping and evaluation of the Paramos groin involved inspection and assessment of post-construction works. Considering that the geologic nature and engineering properties of the materials used to construct coastal engineering structures are critically important to the success and longevity of the structure (e.g., Dupray, 2005; Latham et al., 2006a,b), a lithological map of the armor layer of Paramos groin was first prepared. More than 5,000 rock materials were vectorized, and the different geomaterials were identified (Table 2): for example, natural rocks (granite and gneiss) and artificial materials (concrete or a mixed material [i.e., concrete + aggregates]).

The applied cartography provided an evaluation of the current condition of the structure and of the status of the revetment material. The Schmidt Hammer rebound values provided an estimate of the uniaxial compressive strength of block armor materials along the crown wall of the structure,

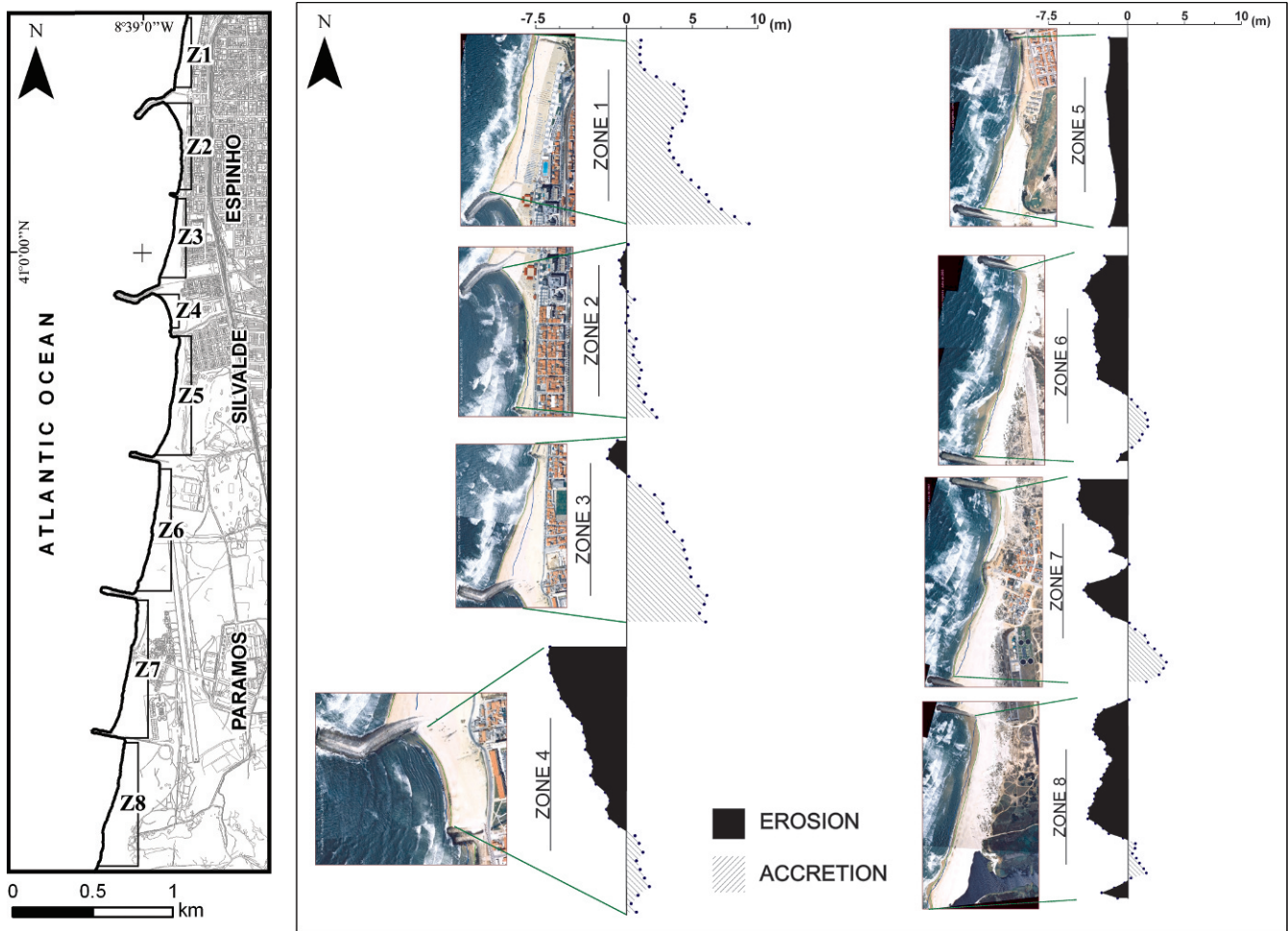


Figure 6. DSAS application on the beach zones studied in the Espinho area: EPR (end point rate) quantification.

according to ISRM (1981). The cross-check of all geotechnical and geomechanical parameters obtained, particularly petrophysical features, weathering grade, and uniaxial compressive strength, allowed us to

classify the Paramos armor block material in terms of its degree of deterioration (Figure 9a). Zone I (ZI) corresponds to the crown wall, which shows the maximum strength (ranging from 195 to 250 MPa).

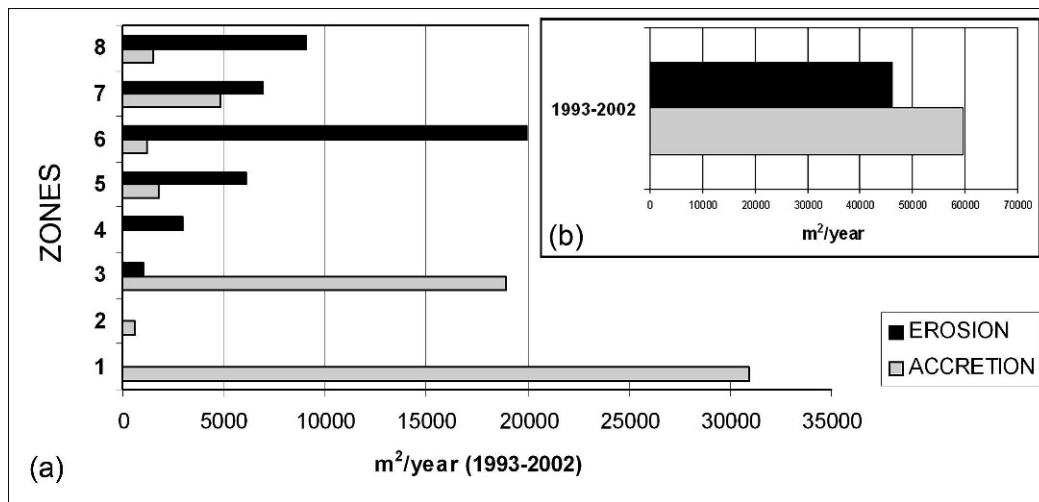


Figure 7. Estimated areas of land loss or gain. (a) Beach zones (1 to 8) area variation; (b) Espinho total area variation.

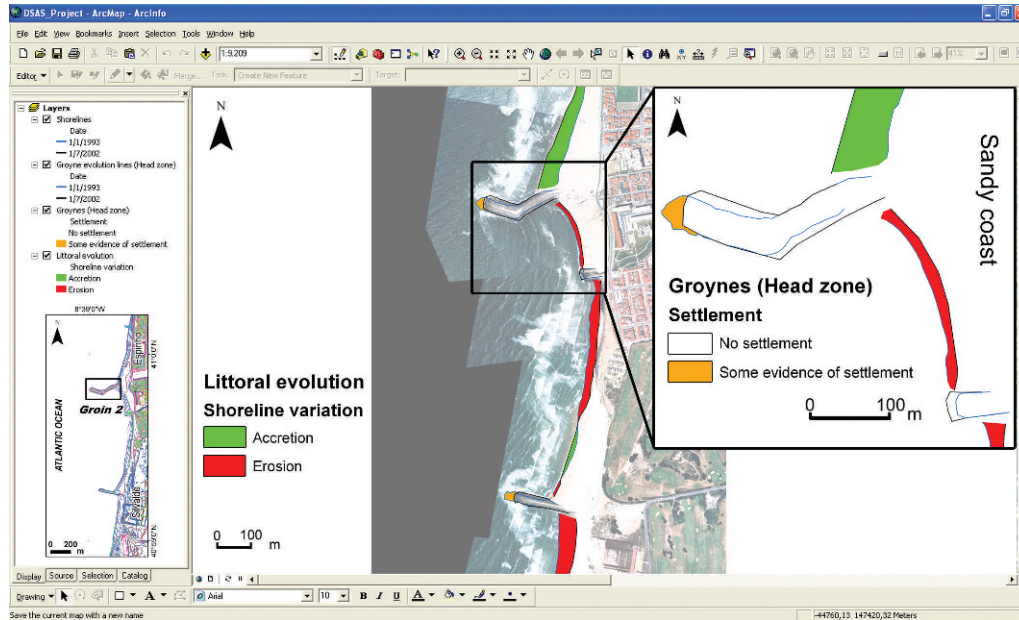


Figure 8. GIS project and application of DSAS extension on Espinho coastal dynamics: example of the settlement studied for groyne 2.

This zone is predominantly composed of medium- to fine-grained reddish-rose granite. Zones II (ZII, inner) and III (ZIII, head) have the same lithologic characteristics, namely medium-grained grayish-blue biotitic granite, with intermediate values of strength, ranging from 150 to 195 MPa. Finally, zone IV (ZIV) corresponds to the outer zone, with the lowest strength values (ranging from 120 to 150 MPa). This zone mainly comprises yellowish biotitic orthogneisses with feldspar mega-crystals. Based on the described methodology, an example of the lithological characterization obtained is presented for Paramos groyne (Sector 5) in Figure 9b.

Table 3 synthesizes the geotechnical features of the armor block material classification and the present

deterioration level of Paramos groyne. In this case, for zones I, II/III, and IV, the deterioration levels are, respectively, very low, medium to high, and low.

The methodology used for the geotechnical mapping and assessment of the block materials from Espinho coastal protection structures proved to be an easy, fast, and economical way to assess the status of coastal protection structures (details in Pires and Chaminé [2007, 2009]). Furthermore, this methodology provides a geological-geotechnical characterization useful for groyne management. The main results of both the applied cartography developed in a georeferenced GIS base and the evaluation of the deterioration level of the groyne materials reinforce the need for careful planning in this kind of work. Because the cost of production and

Table 2. Geomaterials recognized along the superficial layer and studied characteristics for the five sectors.

Description	Geomaterial Characterization			
	Granite	Granite	Biotite-orthogneiss	Concrete
Color	Grayish-blue	Reddish-rose	Yellowish-brown	Gray
Weathering grade (W) (GSE, 1995; ISRM, 2007)	W ₁ -W ₃	W ₁ -W ₃	W ₁ -W ₃₋₄	—
Degradation grade (D)	n.a.	n.a.	n.a.	D ₁ -D ₄
Texture/structure	Medium grained	Medium to fine grained	Coarse to medium grained	n.a.
Observations (geological units, from Chaminé [2000])	Granitic facies, essentially biotitic, grayish-blue, medium grained (Canidelo quarry, “Lavadores” granite)	Granitic facies, reddish-rose, medium to fine grained (Canidelo quarry, “Lavadores” granite)	Biotite orthogneiss (quartz and large feldspar megacrystals) has a strong foliation and a strong shear fabric (Malaposta quarry, “Lourosa” Unit)	Blocks with concrete and aggregates

n.a. = not applicable.

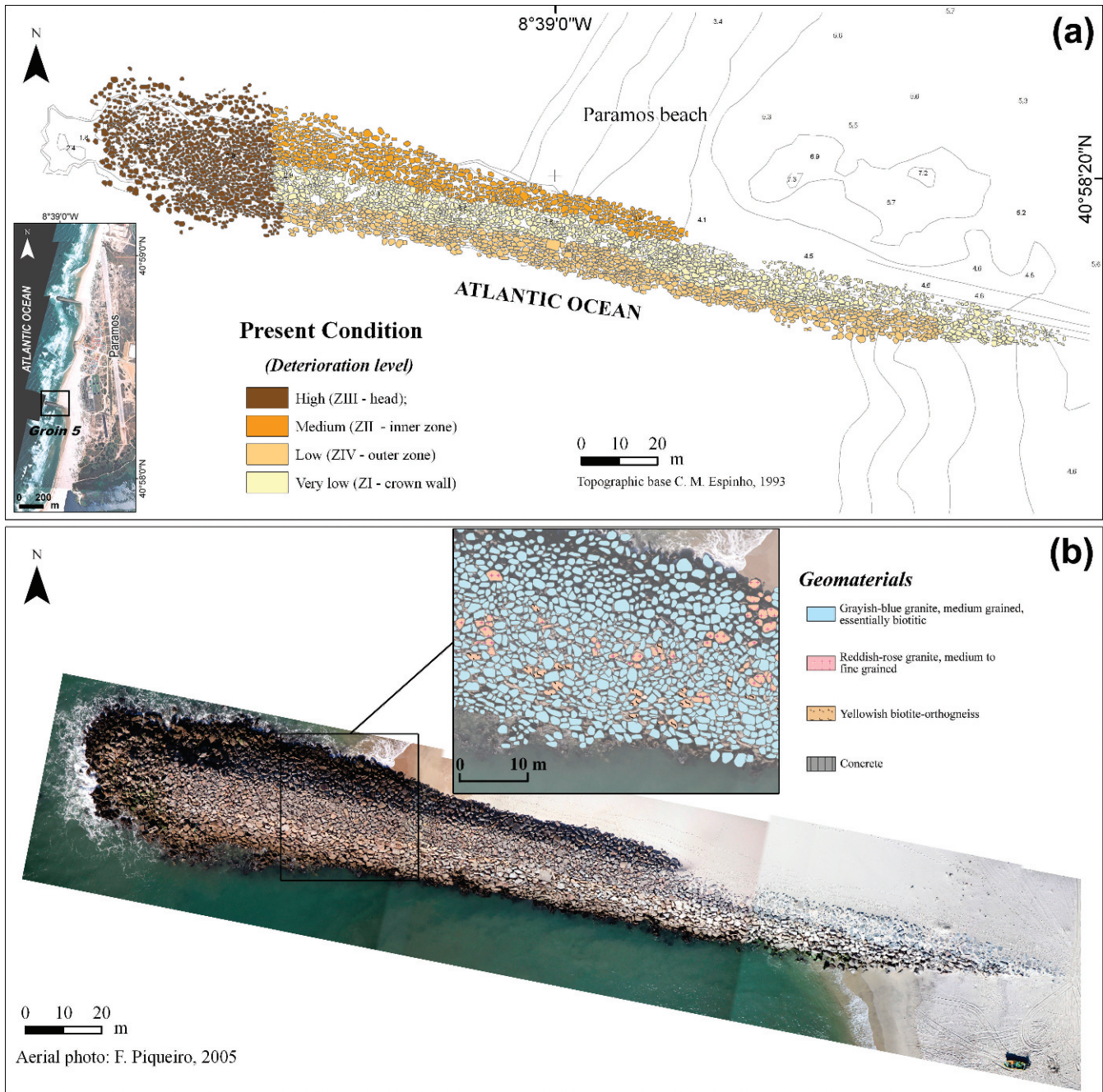


Figure 9. (a) Armor block materials zonation, a tentative synthesis map: deterioration level and structure present condition; (b) Applied cartography from Paramos groin.

Table 3. Results of the field assays and the visual inspection.

Designation	Weathering Grade (W) (ISRM, 1981; GSE, 1995)	Uniaxial Compressive Strength (MPa) (ISRM, 1981)	Present Condition (deterioration level)
ZI	W ₁	195–250 [S ₁]	Very low
ZII/ZIII	W ₁₋₂	150–195 [S ₂]	Medium/high
ZIV	W ₃	120–150 [S ₂]	Low

Z = zone; ZI = crown wall; ZII = inner zone; ZIII = head; ZIV = outer zone.

transportation of the very large quantities of rock often required for coastal and shoreline structures is an essential consideration when selecting a particular design solution, it is important to establish the availability and quality control of rock materials at their point of origin or location of extraction until the project is completed. Further studies to provide more detailed information on the geological materials and the material properties in relation to the design requirements and to apply standard test procedures to assess the quality and durability of these materials before and during construction (Pizarro et al., 2005) are in progress. At the same time, there is also a need to evaluate the structure condition after the construction (i.e., for monitoring and maintenance perspectives).

Several generations of Espinho residents have been living under the threat of coastal hazards. They have thus developed some feeling for coastal erosion, and their general opinion on the coastal defenses of the city of Espinho is that these structures are essential to holding back the sea and enlarging beach dimensions (Soares de Carvalho, 1995; EUrosion, 2004). The Espinho shoreline is a very dynamic coastal stretch, with historic and natural erosion events that may possibly become aggravated in the future, necessitating calls for careful and continued monitoring studies. Such studies may help us to avoid the undesired consequences of possible future aggravations of the erosion process.

CONCLUDING REMARKS

In conclusion, the approach adopted in this work contributes to improving our knowledge of the dynamics of the Espinho shoreline. It provides a solid base from which to easily forecast and model shoreline displacements over the years and to identify main areas of erosion/accretion.

The approach used to propose a coastal evolution for this area indicates that the recession of coastline is occurring in the form of erosive wave propagation from north to south. Along this coastal stretch there are also several hydraulic works that influence the coastal erosion process, and this can easily be shown by considering the accretion that occurs in the northern areas of obstacles (e.g., groins) and the erosion that occurs in the southern areas.

The main erosion problems, which exist in the southern area (downdrift), are due to lack of sediment transport. The most vulnerable area in terms of erosion is the urban seafront of Silvalde/Paramos (zones 4 to 8). Several large groins protect the downdrift of Paramos, and the Coastal Management Plan considers the probable retreat of this urban seafront as a future measure of managed realignment predicted for the Portuguese west coast (Taveira

Pinto, 2003). Consequently, the main problems in this stretch are due to (i) sandy coast with no natural rock protection; (ii) extended erosion problems, with the destruction of the dunes; (iii) large groins and sea walls; and (iv) the erosion existing in the urban seafront of Silvalde/Paramos (considering the retreat of this urban seafront).

In addition, according to the results obtained, a methodological characterization of the geomaterials is crucial to determine the deterioration level and the structures' present condition. This approach uncovered the need for repair/maintenance work in some parts of the study area or for eventual changes in their design. Moreover, the GIS tools provided an easy and very useful way of handling large data sets and, most importantly, of visualizing the results in a way that facilitates the rapid perception of the status of the structures and, thus, the decision-making processes. In the present case, according to the evaluations performed, replacement of the primary armor layer of the head of the structures would increase the effectiveness and modification of the longevity of the structures. The results also indicate that for some of the sectors, alterations to the design of the structures would help minimize deterioration of the structures due to erosion. Figure 9a revealed that the head and inner zones have high and medium deterioration levels, respectively, and that they are significantly susceptible to waves and current events. These two zones comprise geomaterials that do not possess high compressive strength and are also subject to the currents and wave propagations, mainly from north to south, that facilitate the overall damage to the structures. For the five groins studied it was clear that the head zone has the highest level of deterioration and is the most susceptible component of the hydraulic structures, and it was also evident that during the construction and design of these structures, material selection was not based on the type of rock, quality, durability, and other characteristics, which the contractor should have taken into consideration. As a result, the methodology developed provides a geotechnical characterization that is useful in the planning of maritime repair works. Moreover, this methodology gives further support to the importance of establishing the availability and the geotechnical quality and durability of geomaterials to be used at a particular site at the time of extraction from quarries when one is considering geoenvironmental design options (e.g., Lienhart, 1998; Latham et al., 2006a,b; and Manoliu and Radulescu, 2008). On the other hand, there is also a concern for evaluating the structural condition of protection work after the construction for monitoring and maintenance.

The study also provides information valuable in extending the average lifetime of Espinho coastal

protection structures. The costs of such structures, their expected behavior, as well as the consequences of their failure do justify on-site geotechnical investigations designed to help in decision making.

This research is still in progress to provide more detailed information on the most appropriate geomaterials (namely with regard to the rock mechanic properties required in relation to the design) and standard test procedures that are usually applied to assess quality and durability of these materials before and during construction. In this area, the illegal occupation/use of the maritime public domain is common, and there is no cartographic record of the areas of the public shoreline domain, which makes the management of these areas very complicated. To achieve results for the proposed actions or measures, it is essential to study and adequately program the interventions in the littoral region. Thus, there are three essential objectives: (1) to encourage technical scientific studies on the littoral; (2) to identify the areas at risk and take preventive measures; and (3) to protect the areas at risk.

Some proposed solutions can be accomplished through the following processes: recuperation of the dune systems; collaboration with other institutions with littoral jurisdiction; identification and definition of the areas that are more vulnerable to erosion and implementation of preventive measures; implementation of the coastal defense programs; intervention in priority areas (e.g., Espinho); and additional studies to find adequate interventions. The so-called hard coastal defenses are indispensable, and at the moment, there is not any plan to remove the existing groins, seawalls, and other hydraulic structures. Hence, maintenance works, or even rearrangement of the original design of the structures, is likely to continue. In addition, artificial sand nourishment operations might also be included as possible solutions to the erosion problem affecting this coastal stretch.

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REFERENCES

- ARAÚJO, M. A., 1991, *Geomorphological evolution of littoral platform from Porto region*: Unpublished Ph.D. Thesis, Universidade do Porto, 534 p. [in Portuguese]
- ARAÚJO, M. A., 2002, Relative sea level, diastrophism and coastal erosion: The case of Espinho (Portuguese NW coast). In Veloso Gomes, F.; Taveira Pinto, F.; and Neves, L. (Editors), *Littoral 2002*, Vol. 2: Associação Eurocast-Portugal, Porto, Portugal, pp. 125–132.
- ARAÚJO, M. A.; GOMES, A.; CHAMINÉ, H. I.; FONSECA, P. E.; GAMA PEREIRA, L. C.; AND PINTO DE JESUS, A., 2003, Regional geomorphology and geology from the Porto–Espinho sector (W Portugal): morphostructural implications to Genozoic sedimentary cover: *Cadernos Laboratório Xeolóxico de Laxe*: A Coruña, Vol. 28, pp. 79–105. [in Portuguese]
- BAILEY, C. AND GATRELL, A., 1995, *Interactive Spatial Data Analysis*: Addison Wesley Longman, Essex, UK, 410 p.
- BIRD, E., 1997, *Coastal Geomorphology: An Introduction*: John Wiley & Sons, Ltd., Chichester, United Kingdom, 321 p.
- BRUM FERREIRA, A., 1983, Problems of the quaternary geomorphological evolution at NW Portugal: *Cadernos Laboratório Xeolóxico de Laxe*: A Coruña, Vol. 5, pp. 311–329. [in Portuguese]
- BURKE, R.; NAPOLEON, E.; ORMSBY, T.; GROESS, C.; AND FEASTER, L., 2001, *Getting to Know ArcGIS Desktop: The Basics of ArcView, ArcEditor, and ArcInfo Updated for ArcGIS 9*: Getting to Know series. ESRI California, Redlands, California, USA, 550 p.
- CARTER, R. G., 1988, *Coastal Environments*: Academic Press, London, United Kingdom, 617 p.
- CHAMINÉ, H. I., 2000, *Stratigraphy and structure of the Espinho-Albergaria-a-Velha metamorphic belt (Ossa-Morena Zone): geodynamic implications*: Unpublished Ph.D. Thesis, Universidade do Porto, 497 p. [in Portuguese]
- CHAMINÉ, H. I.; GAMA PEREIRA, L. C.; FONSECA, P. E.; NORONHA, F.; AND LEMOS DE SOUSA, M. J., 2003, Tectonostratigraphy of the Porto-Albergaria-a-Velha-Coimbra-Tomar Shear Zone between Central-Iberian and Ossa-Morena Zones (Iberian Massif, W Portugal): *Cadernos Laboratório Xeolóxico de Laxe*: A Coruña, Vol. 28, pp. 37–78. [in Portuguese]
- CIRIA; CUR & CETMEF, 2007, *The Rock Manual: The Use of Rock in Hydraulic Engineering*, 2nd ed.: C683. CIRIA—Centre for Civil Engineering Research, London, United Kingdom, 1200 p.
- CIRIA/CUR—CENTRE FOR CIVIL ENGINEERING RESEARCH, 1991, *Manual of the Use of Rock in Coastal and Shoreline Engineering*: Construction Industry Research and Information Association, Special Publication 83, Centre for Civil Engineering Research and Codes Report 154, CIRIA/CUR Edition, 607 p.
- CUNHA, S.; SILVA, S. R.; AND PIQUEIRO, F., 2006, Photogrammetry in light aircraft. In *Proceedings of the International Calibration and Orientation Workshop, EuroCOW 2006*, Castelldefels, Spain, pp. 25–27.
- DIAS, J. A., 2005, Evolution of the portuguese coastal zone: natural and anthropic disturbance factors: *Revista Encontros*

- Científicos-Turismo, Gestão, Fiscalidade*: Faro, Vol. 1, pp. 7–27. [in Portuguese]
- DIAS, J. A.; BOSKI, T.; RODRIGUES, A.; AND MAGALHÃES, F., 2000, Coast line evolution in Portugal since the Last Glacial Maximum until present: A synthesis: *Marine Geology*, Vol. 170, pp. 177–186.
- DIAS, J. A.; FERREIRA, O.; AND PEREIRA, A. R., 1994, *Synthetic study and diagnosis of the geomorphology and the dynamic sedimentary processes between Espinho and Nazaré coastal areas*: Electronic document, available at <http://w3.ualg.pt/~j dias/JAD/ebooks>. [in Portuguese]
- DINIS DA GAMA, C., 1983, Use of comminution theory to predict fragmentation of jointed rock mass subjected to blasting. In *Proceedings of the First International Symposium on Rock Fragmentation by Blasting*: Balkema, Luleå, Sweden, pp. 563–579.
- DINIS DA GAMA, C., 1995, Aspectos geotécnicos y de fracturación en la explotación de Canteras. In López Jimeno, C. (Editor), Cap. 10 del Manual de Rocas Ornamentales, Entorno Gráfico. S.L., Madrid, Spain, pp. 231–246.
- DUPRAY, S., 2005, *Integrity of Rock Blocks for Armouring of Hydraulic Works: Towards Fullscale Test to Predict Mass Distribution Changes*: Unpublished Ph.D. Thesis, Imperial College Royal School of Mines, 325 p.
- EUROSION, 2004, *Projecto EUrosion, ENV.B.3/SER/2001/00 30*: Electronic document, available at <http://www.euroasion.org>
- FOOKES, P. AND POOLE, A., 1981, Some preliminary considerations on the selection and durability of rock and concrete materials for breakwaters and coastal protection: *Quarterly Journal Engineering Geology Hydrogeology*, Vol. 14, pp. 97–128.
- GOMES, A., 2008, *Geomorphological evolution of littoral platform between Espinho and Águeda*: Unpublished Ph.D. Thesis, Universidade do Porto, 330 p. [in Portuguese]
- GOMES, A.; ASSUNÇÃO, M. A.; AND SOUSA, A., 2006, The littoral of Oporto region (Northwest Portugal), Portugal: Coastal dynamics. In *International Association of Geomorphology 6th Conference, Field Trip A1*, Vol. 4: Associação Portuguesa de Geomorfólogos, Lisboa, Portugal, pp. 19–23.
- GOMES, A.; CHAMINÉ, H. I.; TEIXEIRA, J.; FONSECA, P. E.; GAMA PEREIRA, L. C.; PINTO DE JESUS, A.; PÉREZ ALBERTÍ, A.; ARAÚJO, M. A.; COELHO, A.; SOARES DE ANDRADE, A.; AND ROCHA, F. T., 2007, Late Cenozoic basin opening in relation to major strike-slip faulting along the Porto-Coimbra-Tomar fault zone (northern Portugal). In Nichols, G.; Williams, E.; and Paola, C. (Editors), *Sedimentary Processes, Environments and Basins: A Tribute to Peter Friend, Special Publications of the International Association Sedimentologists (IAS)*, Vol. 38: Blackwell Publishing, Cambridge, UK, pp. 137–153.
- GOMES, N., 1977, Groin construction and design. In *Seminário Sobre Obras de Protecção Costeira (Seminário 210)*: Laboratório Nacional de Engenharia Civil, Lisboa, Portugal. [in Portuguese]
- GONÇALVES, J. A. AND PIQUEIRO, F., 2004, Georeferencing aerial imagery from a non-metric digital camera: application to the W Portugal coast between Figueira da Foz and Nazaré. In *Proceedings/Actas do VIII Encontro de Utilizadores de Informação Geográfica, ESIG'2004*, Oeiras, Portugal, pp. 1–8. [in Portuguese]
- GRANJA, H. M.; RIBEIRO, I. C.; SOARES DE CARVALHO, G.; AND MATIAS, M. S., 1999, Some neotectonic indicators in quaternary formations of the northwest coastal zone of Portugal: *Physics Chemistry Earth A*, Vol. 24, No. 4, pp. 323–336.
- GSE–GEOLOGICAL SOCIETY ENGINEERING GROUP WORKING PARTY REPORT, 1995, The description and classification of weathered rocks for engineering purposes: *Quarterly Journal Engineering Geology Hydrogeology*, Vol. 28, No. 3, pp. 207–242.
- ISRM (INTERNATIONAL SOCIETY FOR ROCK MECHANICS), 1978a, Suggested methods for determining hardness and abrasiveness of rocks: *International Journal Rock Mechanics Mining Science Geomechanics Abstracts*, Vol. 15, pp. 89–97.
- ISRM, 1978b, Suggested methods for the quantitative description of discontinuities in rock masses: *International Journal Rock Mechanics Mining Science Geomechanics Abstracts*, Vol. 15, No. 6, pp. 319–368.
- ISRM, 1981, Basic geotechnical description of rock masses: *International Journal Rock Mechanics Mining Science Geomechanics Abstracts*, Vol. 18, pp. 85–110.
- ISRM, 2007, The complete ISRM suggested methods for characterization, testing and monitoring: 1974–2006. In Ulusay, R. and Hudson, J. A. (Editors), suggested methods prepared by the Commission on Testing Methods, ISRM. Ankara, Turkey, 628 p.
- KAHRAMAN, S., 2001, Evaluation of simple methods for assessing the uniaxial compressive strength of rock: *International Journal Rock Mechanics Mining Science*, Vol. 38, pp. 981–994.
- KATZ, O.; RECHES, Z.; AND ROEGERS, J. C., 2000, Evaluation of mechanical rock properties using a Schmidt Hammer: *International Journal Rock Mechanics Mining Science*, Vol. 37, pp. 723–728.
- LATHAM, J.-P.; VAN MEULEN, J.; AND DUPRAY, S., 2006a, The specification of armourstone gradings and EN 13383 (2002): *Quarterly Journal Engineering Geology Hydrogeology*, Vol. 39, pp. 51–64.
- LATHAM, J.-P.; LIENHART, D.; AND DUPRAY, S., 2006b, Rock quality, durability and service life prediction of armourstone: *Engineering Geology*, Vol. 87, pp. 122–140.
- LCPC (LABORATOIRE CENTRAL DES PONTS ET CHAUSSÉES), 1989, *Les Enrochements*: Ministère de l'Équipement, Laboratoire Central des Ponts et Chaussées, Paris, France, 106 p.
- LIENHART, D. A., 1998, Rock engineering rating system for assessing the suitability of armourstone sources. In Latham, J.-P. (Editor), *Advances in Aggregates and Armourstone Sources, Engineering Geology Special Publication*, Vol. 13: Geological Society of London, Oxford, UK, pp. 91–106.
- LIMA, A., 1979, A brief history of Espinho: *Espinho Boletim Cultural*, Vol. 1, pp. 11–44. [in Portuguese]
- LIMA, A., 1982, Sea invasions at Espinho: *Espinho Boletim Cultural*, Vol. 15/16, pp. 333–341. [in Portuguese]
- LOPES, J. N. T., 1995, The birth of the urban agglomeration, Espinho in the second half of the XIX century: *Actas 1º Encontro de História Local*, Câmara Municipal de Espinho: pp. 101–105. [in Portuguese]
- MANOLIU, I. AND RADULESCU, N. (Editors), 2008, Education and Training in Geo-Engineering Sciences: *Soil Mechanics and Geotechnical Engineering, Engineering Geology, Rock Mechanics*: Routledge, Taylor and Francis Group, Constantza, Romania, 526 p.
- MAOTDR (MINISTÉRIO DO AMBIENTE DO ORDENAMENTO DO TERRITÓRIO E DO DESENVOLVIMENTO REGIONAL), 2008, *Litoral 2007–2013: Avaliação dos Planos de Ordenamento da Orla Costeira e Propostas de Actuação*: MAOTDR, Lisboa, Portugal, 190 p.
- MCCLEESE, W. F., 2000, *REMR Program Overview and Guide: Repair, Evaluation, Maintenance, and Rehabilitation Research Program*: Geotechnical Associates Networks, LLC, Engineer Research and Development Center, U.S. Army Corps of Engineers, Vicksburg, Mississippi, USA.
- MORAN, C. A., 2003, *Spatio-Temporal Analysis of Texas Shoreline Changes Using GIS Technique*: Unpublished M.Sc. Thesis, University of Texas, 117 p.
- MOTA OLIVEIRA, I. B. AND MARTINS, L. M., 1991, Espinho coastal works and beach reconstruction: *Journal of the Portuguese*

- Association of Hydric Resources*, APRH, Vol. 12, No. 1/2, Lisbon, Portugal, pp. 71–88. [in Portuguese]
- MOTA OLIVEIRA, I. B.; TRIGO TEIXEIRA, A.; AND SANCHES DO VALLE, A., 2000, West coast of Portugal: A comparison between project predictions and reality. In *27th International Conference on Coastal Engineering, ICCE'2000*, Sydney, Australia.
- ORTIGÃO, R., 1876, *Portugal beaches*: Livraria Clássica Editora, Lisboa, Portugal, 275 p. [in Portuguese]
- PDM (PLANO DIRECTOR MUNICIPAL), 2004, *Plano Director Municipal da Câmara Municipal de Espinho*: Electronic document, available at <http://www.cm-espinho.pt>
- PERDIGÃO, F., 1931, The coastal works on beaches: *1º Congresso de Engenharia Civil*: Série de artigos do jornal “Defesa de Espinho,” Fevereiro a Abril de 1976. [in Portuguese]
- PIRES, A., 2005, *Systematic monitoring programme of coastal protection works with a geoenvironmental perspective*: the case study of the Espinho groins: Unpublished Graduation Engineering Thesis, Institute of Engineering, ISEP, Porto, 202 p. [in Portuguese]
- PIRES, A., 2007, *Geoengineering and inspection of hydraulic works, from the source (quarry) to the coastal protection structure*: Unpublished Master Engineering Thesis, University of Aveiro, 268 p. [in Portuguese]
- PIRES, A. AND CHAMINÉ, H. I., 2007, Geotechnical mapping evaluation of rock groynes in Espinho area (NW Portugal). In Ribeiro e Sousa, L.; Olalla, C.; and Grossmann, N. F. (Editors), *Proceedings of the 11th ISRM Congress of the International Society for Rock Mechanics*. Vol. 1: Francis & Taylor Group, Lisbon, Portugal, pp. 307–310.
- PIRES, A. AND CHAMINÉ, H. I., 2009, Geoenvironmental field techniques for rock characterization of coastal protection structures. In Hudson, J. A.; Tham, L. G.; Feng, X.-T.; and Kwong, A. K. (Editors), *Proceedings of SINOROCK'2009, ISRM International Symposium on Rock Mechanics, Rock Characterization, Modelling and Engineering Design Methods*: University of Hong Kong, Hong Kong, China, pp. 262–266.
- PIRES, A.; CHAMINÉ, H. I.; GOMES, A.; PIQUEIRO, F.; MIRANDA, F. S.; AND ROCHA, F. T., 2009, Cartography and assessment of hydraulic structures from Espinho coastal area (NW Portugal) using high-resolution aerial imagery surveys and a GIS interactive base: *Journal Coastal Research*, Vol. SI 56, pp. 1572–1576.
- PIRES, A.; SANTIAGO MIRANDA, F.; GOMES, A.; AND CHAMINÉ, H. I., 2006, Mapping and assessment of groins from the Espinho area: a methodological proposal in geotechnical perspective: In *Proceedings from the National Congress on Geotechnics, Portuguese Society of Geotechnics*, Vol. 1: SPG, Lisbon, Portugal, pp. 165–174. [in Portuguese]
- PIRES, A.; VINAGRE, A.; GOMES, A.; AND CHAMINÉ, H. I., 2007, GIS application to landscape management of the Espinho urban area: a prediction based on historical analysis of coastal dynamics: *Portuguese Association of Geomorphology Publications: APGeom*, Vol. 5, pp. 281–291. [in Portuguese]
- PIZARRO, S.; GOMES, L.; DINIS DA GAMA, C.; LOPES, A.; AND CHAMINÉ, H. I., 2005, Application of optical systems to the evaluation of size distributions in granitic rocks for aggregates production: Malaposta Quarry case study (NW Portugal): *Cadernos Laboratório Xeológico de Laxe*: A Coruña, Vol. 30, pp. 57–73. [in Portuguese]
- SANTOS, J.; NEVES, M.; AND SILVA, L. G., 2003, Rubble-mound breakwater inspection in Portugal: In *Proceedings of Coastal Structures 03 Conference*, Melby, J. F. (Editor), ASCE Portland, Oregon, USA, pp. 249–261.
- SILVA, L. G., 1996, Systematic observation of rubble mound breakwaters in the portuguese coast: *Journal of the Portuguese Association of Hydric Resources (APRH)*, Vol. 17, No. 1, pp. 13–24. [in Portuguese]
- SNIRLIT, 2002, *National Information System of Littoral Resources of the Water Institute*: Electronic document, available at <http://geo.snirh.pt/snirlit/site/consulta.php>
- SOARES DE CARVALHO, G., 1995, Geological story of the Espinho coastal zone in the past 30,000 years: *Actas 1º Encontro de História Local*: Câmara Municipal de Espinho, pp. 155–168. [in Portuguese]
- SOMAGUE, 1980, *Defence works of Espinho region, Pre-project assessment and working plan*: National Harbour Authority: DGP-Direcção Geral de Portos. Unpublished technical report. [in Portuguese]
- TAVEIRA PINTO, F., 2003, *Good Practices in Coastal Zone Management and Coastal Defence*: International Workshop, 7–8 June 2002. FCT/EUCC/IHRH/FEUP, Porto, Portugal, 109 p.
- TEIXEIRA, C.; PERDIGÃO, J.; AND ASSUNÇÃO, C. T., 1962, *Explanation notice from the 13-A sheet (Espinho)*, *Geological Map of Portugal, scale 1:50000*: Geological Services of Portugal, Lisboa, Portugal, 28 p. [in Portuguese]
- THIELER, E. R. AND DANFORTH, W., 1994, Historical shoreline mapping (II): Application of the digital shoreline mapping and analysis systems (DSMS/DSAS) to shoreline change mapping in Puerto Rico: *Journal Coastal Research*, Vol. 10, No. 3, pp. 600–620.
- THIELER, E. R.; HIMMELSTOSS, E.; AND MILLER, T., 2005, *User Guide & Tutorial for the Digital Shoreline Analysis System (DSAS) Version 3.2. Extension for ArcGIS v.9.0*: Part of USGS Open-File Report 2005–1304. 33 p.
- TRIGO TEIXEIRA, A., 2003, Mapping land at risk. Evolution of the Portuguese coast between Espinho and Cape Mondego (1970–1996): *Good Practices in Coastal Zone Management and Coastal Defence*: FCT/EUCC/IHRH/FEUP, Porto, Portugal, pp. 51–63.
- USACE (U.S. ARMY COASTAL ENGINEERING RESEARCH), 1990, *Side Scan Sonar for Inspection of Coastal Structures, REMR Technical Note CO-SE-1.4*: U.S. Army Coastal Engineering Research Center, U.S. Army Corps of Engineers WES.
- USACE, 1995, *Coastal Engineering Manual. Coastal Geology*: U.S. Army Corps of Engineers, Washington, DC, EM 1110-2-1810.
- USACE, 2002, *Engineering and Design, Hydrographic Surveying, EM 1110-2-1003*: U.S. Army Coastal Engineering Research Center, Department of the Army.
- VELOSO GOMES, F.; BARROCO, A.; RAMOS PEREIRA, A.; SOUSA REIS, C.; CALADO, H.; GOMES FERREIRA, J.; CONCEIÇÃO FREITAS, M.; AND BISCOITO, M., 2006a, *Basis for a national strategy for integrated coastal zone management in Portugal*: National Working Group designated by the Ministry for Environment, Spatial Planning and Regional Development (MESPRD), Version for public discussion, 23 January 2006, 62 p. [in Portuguese]
- VELOSO GOMES, F.; TAVEIRA-PINTO, F.; BARBOSA, J.; NEVES, L.; AND COELHO, C., 2002, High risk situation in the NW Portuguese Coast: Douro River, Cape Mondego. In *Proceedings of the 6th International Symposium LITTORAL 2002*, Eurocoast, Porto, Portugal, pp. 411–421.
- VELOSO GOMES, F.; TAVEIRA-PINTO, F.; NEVES, L.; AND BARBOSA, J., 2006b, Pilot site of River Douro, Cape Mondego and case studies of Estela, Aveiro, Caparica, Vale do Lobo and Azores: *EUrosion, A European Initiative for Sustainable Coastal Erosion Management*: EUROSION-PORTUGAL, 316 p.
- VELOSO GOMES, F.; TAVEIRA PINTO, F.; NEVES, L.; AND PAIS BARBOSA, J., 2003, Characterization of the west coast of Portugal. Stretch River Douro (Porto), Cape Mondego: *Good Practices in Coastal Zone Management and Coastal Defence*: FCT/EUCC/IHRH/FEUP, Porto, Portugal, pp. 29–50.
- ZUQUETTE, L. V. AND GANDOLFI, N., 2004, *Geotechnical cartography*: Oficina de Textos, Brasil, 189 p. [in Portuguese]