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Evolution of Coastal Works in Portugal and their Interference with Local Morphodynamics

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ABSTRACT

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Coastal zones are dynamic areas undergoing continuous changes in response to natural and anthropogenic actions. In the paper an overview of the different types of coastal defense works built in Portugal will be presented, giving special attention to their evolution during the last decades, the main problems affecting them, and how experience gathered with previous works has been included in current design practices. The role of numerical models as a mean to understand and to foresee coastal systems' morphodynamics will be also discussed. The importance of numerical modeling as an effective decision support and design tool will be stressed based on examples from the Portuguese coast. The interference of coastal works with local morphodynamics will also be discussed using GIS techniques applied to Portuguese case studies.

ADITIONAL INDEX WORDS: *Coastal structures, Erosion, Coastline evolution models, GIS techniques.*

INTRODUCTION

Coastal zones are highly attractive to man, playing an important role in the economical, social and political development of many countries. Portugal, with more than 800 km of continental Atlantic coast, is no exception to this reality. Nevertheless, several stretches of the Portuguese coastline are permanently threatened by erosion and flooding, endangering man's assets (buildings, roads, etc.) as well as natural systems. These threats will become even more serious in the near future as a consequence of the increasing human-induced changes (construction of dams, harbor breakwaters, navigation channels, dredging works), the proximity of several consolidated urban areas to the sea, accelerated sea-level rise and other possible climate change effects.

Over the last century and up to the present, coastal defense works (CDWs) have become ubiquitous features of Portuguese coastal landscapes as a response to those threats, especially along the most critical waterfronts. Different types of CDWs have been carried out to protect the shoreline against coastal erosion and flooding, which can be classified as "hard" and "soft" interventions. "Hard" interventions are supposed to be build with materials which shall stay permanently in a fixed structure (e.g. groins, revetments). Artificial sand nourishment of beaches and dune restoration can be classified as "soft" interventions.

Coastal engineering works have been studied, tested and constructed in Portugal for more than 100 years (VASCO COSTA *et al.,* 1996). Developments have been made on this subject during this period of time and the experience gained from the preceding works has been incorporated in the design of new CDWs and in the reconstruction of existing ones.

The interference of coastal works with local morphodynamics can be assessed through the comparison of the present conditions (after the intervention) with the expected situation if the intervention was not carried out. The application of numerical models, namely coastline evolutions models, allows the simulation of the shoreline evolution under different scenarios. These models can also be a valuable tool to support decision making processes and to be integrated in the design of new CDWs.

Shoreline evolution and local morphodynamics can also be studied using GIS techniques. The analysis of georreferenced photographs taken at different stages (before and after the works are carried out) and hydrographic surveys allows studying the evolution of the coast and characterizing the influence of coastal works on local morphodynamics.

PORTUGUESE COAST AND ENVIROMENTAL CONDITIONS

The Portuguese continental coast comprises two main stretches: one is facing west (about 640 km long), and the other is facing south (about 170 km long). The Portuguese coast is mostly a sandy shore, with a large number of siliceous sandy beaches. There are also some rocky and cliffed stretches (Figure 1).

Tides are of the semi-diurnal type, reaching amplitudes that range between 2 m and 4 m during spring tides. The wave climate is highly energetic in the Portuguese west coast. The main storms come from the North Atlantic, mainly between the months of October to March. The most frequent significant wave heights are in the range of 2 m to 3 m, but during storms significant wave heights may exceed 8 m (once per year), persisting for up to 5 days. The most frequent wave periods are in the range of 8 s to 12 s, reaching 16 s or 18 s during storms. Wave directions between west and northwest prevail, with also some occurrences from southwest. The southern Portuguese coast has a milder wave climate, with some periods of calm. The significant wave height is seldom above 4 m. The prevailing wave directions are the southwest and the southeast.

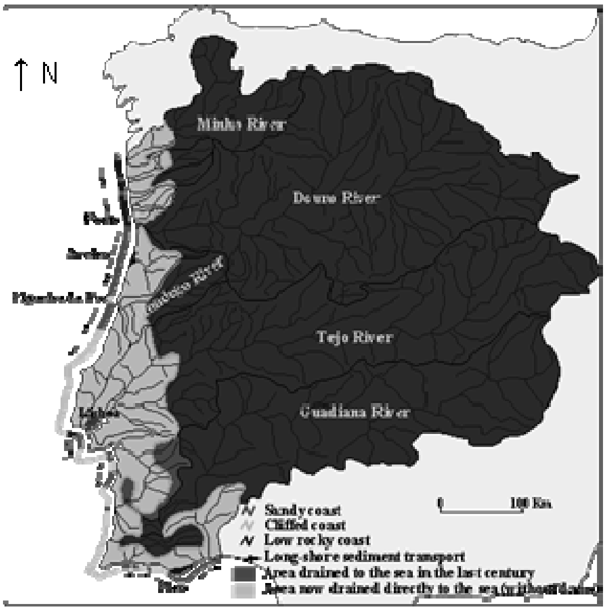

Figure 1. Geological and littoral drift characteristics in the Portuguese coast. Evolution of areas drained to the sea without damming in the last century compared to the present (VELOSO-GOMES *et al*., 2006).

On the Portuguese west coast, owing to the dominant wave direction, the potential alongshore sediment transport is usually south directed (with some exceptions between Lisbon and Sines), with an intensity of about 1-2 million m^3/year. On the southern coast the alongshore sediment transport is eastward directed and has a smaller intensity. The most important sediment sources are rivers and coastal erosion. The contribution coming from the rivers has been decreasing over time, essentially due to dam construction (Figure 1) (either in Portugal or Spain) and sand extraction, for construction and navigation purposes. As a result, coastal erosion has been increasing.

Due to the specific and severe climate characteristics referred above, it is necessary to protect some critical stretches of the Portuguese coastline with defense works. VASCO COSTA *et al*. (1996) states that serious coastal protection problems usually arise from the simultaneous occurrence of 4 m spring tides with significant wave heights higher than 8 m. These situations can occur every year during winter season.

PORTUGUESE COASTAL DEFENSE WORKS

Coastal erosion is a serious problem of growing intensity in Portugal. This is essentially due to the human action (construction of dams, harbor breakwaters, navigation channels and dredging works), the sea level rise and the proximity of several consolidated urban areas to the sea because of the lack of coastal management policies in the past (VELOSO-GOMES *et al*., 2006).

Along the most critical waterfronts of the Portuguese coast, several CDWs have been built through the years, Figure 2. At the present, the main CDWs with influence on the defense of the coast are the groins, the revetments, and the artificial sand nourishment of beaches, the dune restoration interventions and the harbor rubble-mound breakwaters. The "hard" defense structures, such as groins and revetments, are sometimes complemented by "soft" interventions namely artificial sand nourishment of beaches.

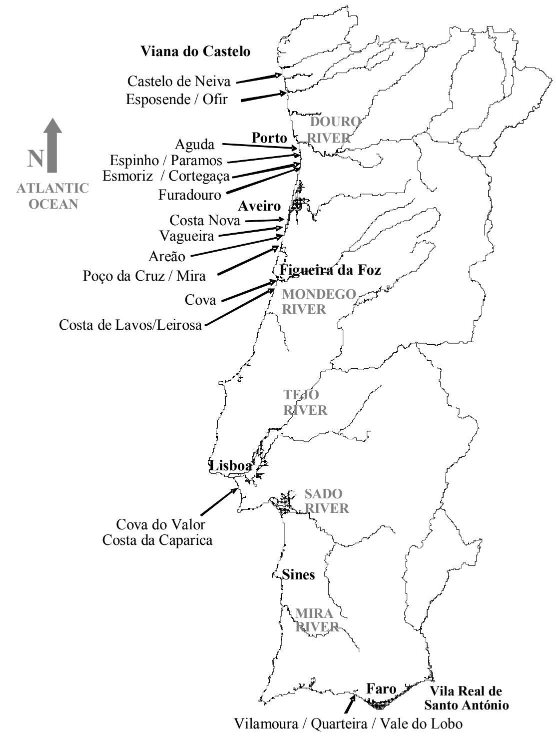

Figure 2. Location of the most important coastal defense works in the Portuguese coast.

The reconstruction works of the Costa da Caparica groin field are an example in which these kind of complementary measures have been used. In this project it is foreseen to nourish artificially the beach with 3 Mm^3 of sand between 2007 and 2010. Vale do Lobo beach - Algarve, has also been artificially nourished with 0.7 Mm^3 of sand between October 1998 and January 1999 and again in 2007. The referred strategy allows a better preservation of the natural characteristics of the coast, reducing the use of heavy coastal protections. One drawback issue of this approach is the necessity of periodic maintenance with its associated costs.

Harbor rubble-mound breakwaters are not built with the purpose of protecting the coastline. However, due to their length and orientation, breakwaters have a large impact on the coastline by trapping the sediments in their updrift side leading to shoreline retreat in the downdrift side. Breakwaters of Viana, Aveiro and Figueira harbors are examples of locations where these situations have occurred. Detached breakwaters have also been built on the Portuguese coast, namely near Castelo de Neiva and Aguda beach.

Coastal dunes, resulting from the accumulation of marine sand transported by the sea and the wind actions, have an important role in the protection of the inner low lying adjacent land in some stretches of the Portuguese coast. These natural morphologies are being affected by coastal erosion, resulting in the destruction of some stretches of these systems. Since 2000 dune restoration interventions have been carried out along significant extensions.

Portuguese "hard" structures are usually built with natural stones and/or artificial concrete blocks. Most of these works are made with stones with weights up to 12 t. Beyond this limit, artificial blocks are used, being the tetrapods and the cubes the most used. Its weights can vary between 15 t and 90 t, being the more weighted blocks used exclusively in the construction of harbor breakwaters.

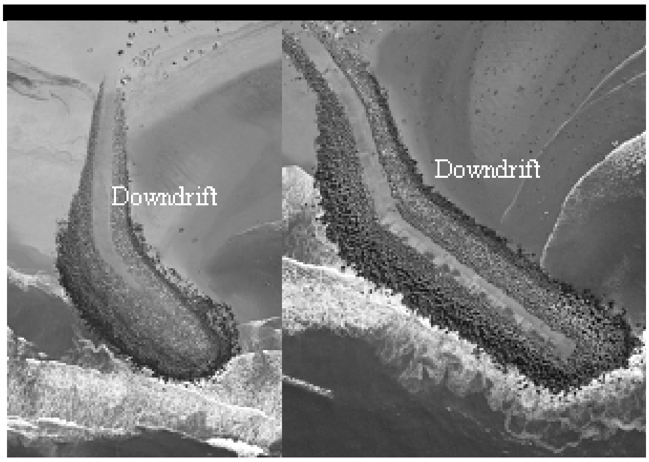

Figure 3. Examples of Portuguese groins: Areão (2005) – left; Espinho Norte (2005) – right.

Groins have a typical symmetrical trapezoidal cross section, with an armor layer, an underlayer and a core. The armor layer is in general composed of natural stones. The rough wave climate, the large tidal range and the need to build long groins in order to intercept part of the alongshore sediment transport, expose these CDWs to important forcing loads. Some of these structures can have more than 300 m in length and depths of 5 m bellow chart datum (CD) are easily reached. The use of artificial concrete blocks is therefore required in some structures, especially at the head. Tetrapods of 300 kN have been used in the armor layer of two “S” shaped groins located in Espinho city, Figure 3.

Portuguese groins are usually linear, but sometimes can have a more complex configuration to allow the creation of a diffraction beach downdrift and, therefore, the mitigation (to some extent) of the local negative impacts induced by these structures. Other configurations include the “S” shaped (north and central groin of Espinho) and the curved (Areão and Poço da Cruz), Figure 3.

Revetments are heavy interventions made of stone blocks, used to maintain the coastline at a preset alignment, especially at very critical locations, where it is fundamental to protect consolidated urban seafronts. Despite the size of the blocks used maintenance operations are required from time to time.

Coastal defense works, aiming to protect vulnerable stretches of the coast against erosion, are themselves affected by this phenomenon. Figure 3 shows, as an example, the damages occurred at the head of the north groin of Espinho. It is important to mention that this structure has been repaired in 1997 and a new repair intervention is foreseen during 2009.

The rough environmental conditions and the sandy foundation are important drawback issues for many of the Portuguese CDWs. This leads to a significant increase of the investment, either in the initial construction of these works or on their future maintenance and reconstruction operations. At the groin’s head, bathymetry can change between 1 m and 4 m bellow CD, along the year (VELOSO-GOMES and TAVEIRA-PINTO, 2000).

In the design of new CDWs, as well as in the maintenance and reconstruction of the existing ones, the experience gathered during preceding works has been incorporated. Interventions carried out recently on several CDWs included: lowering of the structure armor layer foundation, use of smaller slope angles, increase of stone’s weights, increase of the superstructure crest width and elevation of the crest level, artificial sand nourishment operations, use of a filter layer under the armor layer and consideration of toe berms.

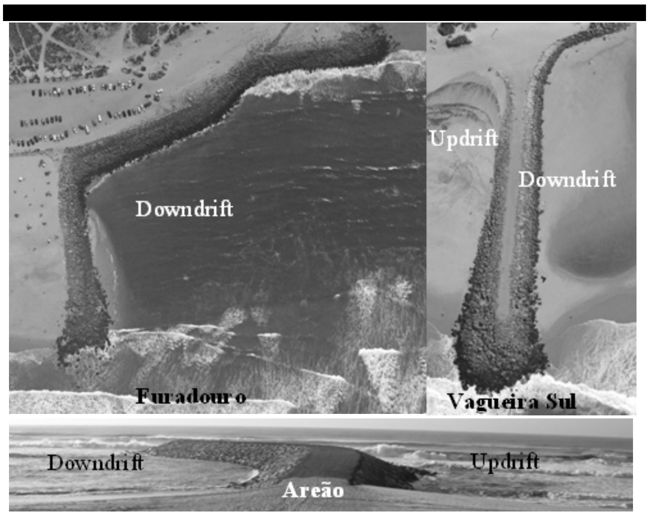

Figure 4. Alternatives to deal with groins root flanking and shoreline retreat downdrift the structures.

It is important to have in mind that risks related with exposure to the sea action may be locally and temporally reduced by the CDWs but they are not completely eliminated, as some critical situations that have been documented demonstrate. Therefore, the existence or the possible construction of coastal defense structures should not be used as an excuse to allow building in areas at risk.

The effects arising from the construction of groins are essentially characterized by the trapping of sediments in their updrift side, leading to downdrift beach/seabed lowering and shoreline retreat. Flanking of the structure root may be expected in some situations, as prior experience demonstrates. The protection against groins’ root flanking can be assured, to some extent, by the extension of the downdrift rubble-mound slope, following the coastline alignment. It is also possible to design the superstructure of the groin with a reduced crest elevation in order to allow sand by-passing, over the structure, from the updrift to the downdrift side. The use of curved head configurations with the aim of creating a diffraction beach downdrift is also a possibility. Figure 4 shows three structures in which these concerns have been taken into account.

Recognized the important role of the armor layer support on the stability of the whole structure, Portuguese coastal defense structures are nowadays being build (and repaired) with toe berms. Toe berm design is carried out taking into account the anticipated settlement and sliding of the toe berm blocks, due to scour effects and the dynamic behavior of the forcing loads, resulting in toe berms clearly visible during the first years after construction.

NUMERICAL PERSPECTIVE IN COASTAL DEFENSES FUNCTIONAL DESIGN

It is established that modeling is crucial, not only to understand and to foresee the morphodynamics of the coastal systems, but also for effective decision making and efficient solution selection for complex problems of the coastal zones. Progressively more sophisticated, the models lead to advances in the understanding of several coastal characteristics and of the involved physical processes (LAKHAN, 2003).

Numerical models should be used to estimate coastline changes (e.g. COELHO, SILVA and VELOSO-GOMES, 2006a and COELHO, VELOSO-GOMES and SILVA, 2006b) around groins, groin fields, revetments and detached breakwaters. Bypassing, structure permeability, as well as net and gross alongshore transport are key

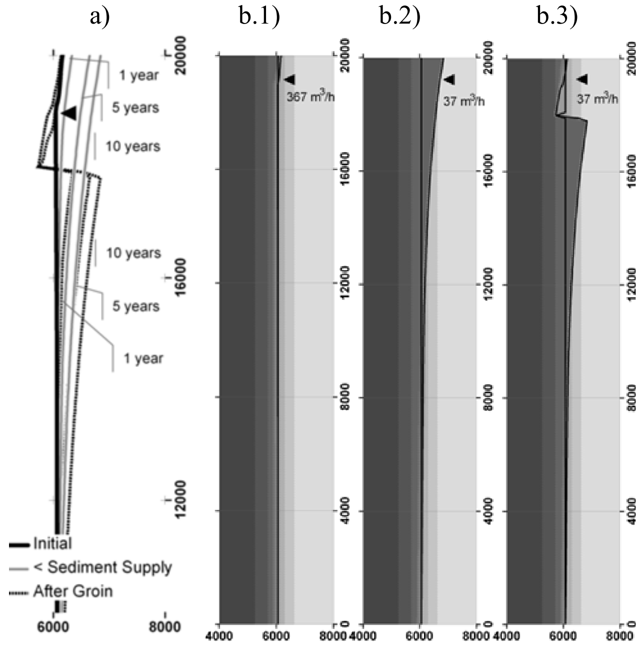

Figure 5. Plan view of (a) coastline evolution as predicted by LTC model in 10 years for each of the situations: (b.1) beach in equilibrium with a constant sediment supply in the upper part of the domain; (b.2) sediment supply reduction to 10 %; (b.3) groin construction (SILVA *et al*., 2007).

Figure 6. Coastline evolution scenario (line) in a 10 year horizon over initial orthophotomap basis from 1996 (COELHO, VELOSO-GOMES and SILVA, 2006b).

factors in the functional design. Monitoring programs should be established, in order to address the project success, and to allow the creation of reaction mechanisms, that would permit changes in the structures, if unacceptable impacts arise.

Numerical modeling assumes an important role in the planning and design processes of CDWs including beach nourishment projects. In the planning phase, models should be used in order to evaluate and forecast the morphodynamic conditions that would occur if nothing had been done, Figure 5. Their use is also a powerful technique to help in the selection of a solution among alternatives, to face a specific coastal problem, and evaluating the effects of the different scenarios inherent to each solution. After construction, if a monitoring plan has been established, numerical modeling may be of help to judge the success of the project, allowing the comparison of the actual morphodynamic conditions with the expected if no intervention had been made.

Monitoring in coastal projects is essential for numerical models refinement and improvement. One of the main limitations in coastal models development is the lack of data to calibrate them. Most of the present models are validated with ideal situations and, when applied to real cases, they are gagged through specific data. After having gagged, the models are applied in a differentiated way, in analysis situations, evaluation of scenarios and forecast of future conditions.

In the LTC model (COELHO, SILVA and VELOSO-GOMES, 2006a and COELHO, VELOSO-GOMES and SILVA, 2006b) one line modeling concept has been extended in order to achieve long-term predictions of coastline evolution, as well as to support and deliver better coastal engineering solutions for erosion control. Rule-based modeling was adopted for cross-shore distribution of sediments along the active profile. The model is especially designed for sandy beaches, where the main cause of coastline evolution is the alongshore sediment transport, which depends on the wave climate, water levels, sediment sources and sinks, sediment characteristics and boundary conditions. The model assumes that each wave acts during a certain period of time and is able to distribute erosion or accretion resulting from alongshore transport along the active cross-shore profile, between the closure depth and the wave run-up limit. The model inputs are the changing water level and the topography of the landward adjacent zones, which is changed during calculation. Moreover, different coastal works combinations may be considered with almost no limitation for the number of groins, breakwaters, seawalls, sediment sources sites or artificial nourishments. Extensive areas can be represented up to 50 years.

The behavior of different coastal defense solutions has been tested by the application of the LTC model to generic situations (COELHO, SILVA and VELOSO-GOMES, 2006a). The model has also been applied to two Portuguese northwest coastal stretches: Aveiro and Figueira da Foz, (COELHO, VELOSO-GOMES and SILVA, 2006b). The results allowed a qualitative evaluation of the main potential consequences of the ongoing erosion. There are already several hard coastal defenses protecting the existing settlements in both coastal stretches.

It is expected that certain structures will require maintenance works and in some cases changes in their design will be needed. Adequate monitoring plans are essential in keeping the maintenance costs of the structures at a low level. In both coastal stretches the model results have shown an erosion tendency, with coastline retreat downdrift the harbors. In the case of Aveiro coastal stretch susceptible areas and zones where sand spit disruptions are to be expected were identified. The application of the model to Figueira da Foz coastal stretch (Figure 6) has shown that much is yet to be done for its improvement. An intense sand

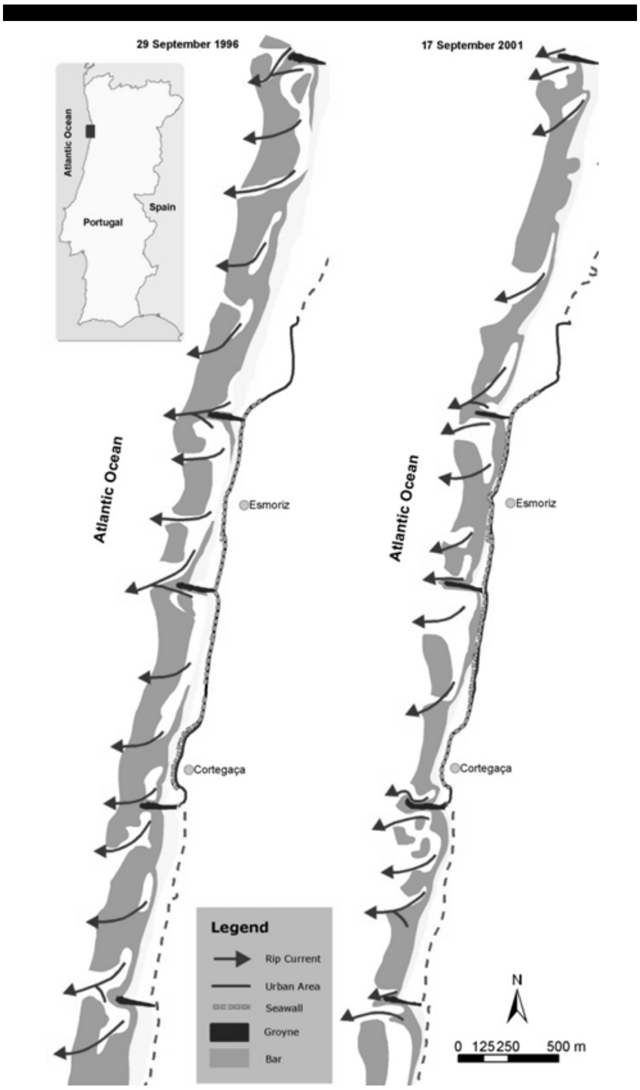

Figure 7. Evolution of the local morphology between Esmoriz and Cortegaça.

accumulation and retention was found in Figueira da Foz beach updrift the harbor.

INTERFERENCE WITH LOCAL MORPHODYNAMICS AND SUMMARY

Coastal structures have important impacts on the beaches and surf zone morphodynamic processes. They influence the refraction/diffraction patterns, limiting the development of alongshore currents, rips and rip feeder currents. Most of the Portuguese coastal structures have important dimensions (length and width) and are normal to the shore. They cross the beach area, extending throughout the surf zone and interfering with the alongshore sediment transport carried by drift currents. This interference could be characterized by downdrift erosion and updrift accretion, beach realignment due to the wave refraction/diffraction around the groins, and formation of rip currents.

In several stretches of the Portuguese coast, morphology and shape have been modified due to the presence of coastal structures. Aguda beach is one of those places, where a detached breakwater was constructed between 2001/2002. From the analysis of aerial images datasets over time (before and after the construction of the detached breakwater), some considerations can be drawn. After the construction of the detached breakwater, the morphodynamic changes start to show, being characterized by typical updrift accretion and downdrift erosion. However, the fast updrift accumulation of sediments in the initial stage occurred not only due to natural reasons, but also due to construction factors.

To construct the detached breakwater it was necessary to build a temporary groin, which triggered the updrift accretion. After the breakwater construction this groin was dismantled but, for public safety reasons (summer season), the sand accumulated in the updrift side was not completely removed. For this reason, the strip between the coastline and the coastal structure, designed to minimize the interference with the alongshore current, was significantly reduced in width, resulting in a tombolo formation.

The evolution of the local morphology between Esmoriz and Cortegaça is represented in Figure 7, which results from the analysis of two aerial image datasets (1996 and 2001). Along this stretch there are two settlements protected by groins and a revetment. The groin spacing along this coastal stretch is 1850 m, 850 m, 1100 m, and 975 m, from north to south. Figure 7 shows the groins' influence on the beach morphodynamics. The changes of alongshore sediment transport lead to the realignment of the coastline (e.g. coastal stretch between the two last groins). Groins may also have an important role on the formation of rip currents, especially if the wave's direction is oblique and the groins are wide spaced (rip currents against both groins and central rips). These are characteristics of the studied area.

Numerical models are important tools not only to understand and to foresee the morphodynamics of coastal systems, but also for effective decision making and efficient solution selection. GIS are also valuable techniques to analyze and to help understanding morphodynamics changes in the coastal zones.

Portuguese coastal defense works were characterized and current design practices presented in the paper. Examples were given to support discussion.

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