DETACHED BREAKWATERS AS COASTAL DEFENSE STRUCTURES: CONFIGURATION EFFECT IN THE ADJACENT COASTLINE

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Abstract

The Portuguese coastline is often submitted to high energy levels, resulting from the action of the sea, so its protection assumes, presently and in some places, an urgency character. An efficient management of the coastal zone should be based on a thorough knowledge of reality, particularly of the wave-structure interaction. It is necessary to consider all possible solutions, highlighting their benefits and trying to minimize their negative effects.

A series of studies, which have been carried out on the Hydraulics, Water Resources and Environment Division (SHRHA), of the Civil Engineering Department (DEC), of Faculty of Engineering, University of Porto (FEUP), aim to evaluate the efficiency of detached breakwaters as coastal defence structures of the west coast of Portugal. Firstly, a detached breakwater was proposed for the defence of the urban front of Espinho, located on the northwest coast of Portugal. Following this study, numerical simulation of the hydrodynamic and the morphodynamic conditions were performed, using the SMC (Sistema de Modelado Costero) software, developed in Cantabria University to support coastal zones management. The present situation was compared with a scenario of implantation of the proposed breakwater. Simulation results suggested the need to test different configurations for the detached breakwater. Afterwards, a physical modelling research study was conducted in order to analyze the effect of different configurations of coastline parallel detached structures in the adjacent coastline/beach. Moreover, the configuration optimization was sought in order to reduce negative effects, for typical conditions of the northwest coast of Portugal.

In this article, important aspects of these studies are presented and discussed.

Detached Breakwaters as Coastal Defence Structures

General Characteristics

Detached breakwaters are used as shore and coast protection measures. These structures may also serve for guiding currents, for the confinement/protection of estuaries, for setting navigation channels and for coastline stabilization. They exist in the emerged and submerged form and may take various configurations according to the objective.

As coastal defence structures, detached breakwaters effectively combine the protection and the increase of sandy beaches' areas. Its functioning consists on the incident wave energy reduction. Indeed, they act as barriers to the incident wave propagation, giving rise to diffraction phenomena near their ends. The energy reduction provided by reflection and breaking phenomena is compensated by a lateral transfer of energy, from the exposed side of the structure to the sheltered area. These processes are accompanied by the formation of recirculation currents in the sheltered area that promote sediments' transport and subsequent morphological readjustment, in between the structure and the coastline. For a nearly orthogonal incidence of the sea waves in a detached breakwater parallel to the coastline, morphological features develop through the accumulation of sediments in a direction almost perpendicular, from the coastline or the structure (salient). A permanent connection between the two may be established (tombolo).

This type of structure is commonly used in regions where the wave climate is moderate. In fact, because of their function of reducing the incident wave energy, they are exposed to significant forcing loads, making them expensive to build and having major maintenance costs. On the northwest coast of Portugal (rough wave climate) these structures may become costly, due to its high exposure level, the need to be constructed, in general, by sea and to the high volumes of material required (Taveira-Pinto, 2002). Nevertheless, there are two examples of this kind of structure lying on this coast, in Aguda and Castelo de Neiva.

Espinho Urban Water Front Coastal Defence

The city of Espinho, a major touristic pole of the northwest coast of Portugal, has been repeatedly attacked by the sea since the late 19^{th} century. In fact, between 1880 and 1911 the coastline retreated 225 m. Several defence interventions have been needed and built since then. In the early 80's four large groins were built, of which only the two larger (north groin, with about 350 m in length and south groin, about 400 m) were maintained. In 1997 these two structures were repaired and reinforced (Veloso-Gomes *et al.*, 2006). However, this intervention did not definitively solve the erosion problem on Espinho urban water front (Figure 1, left).

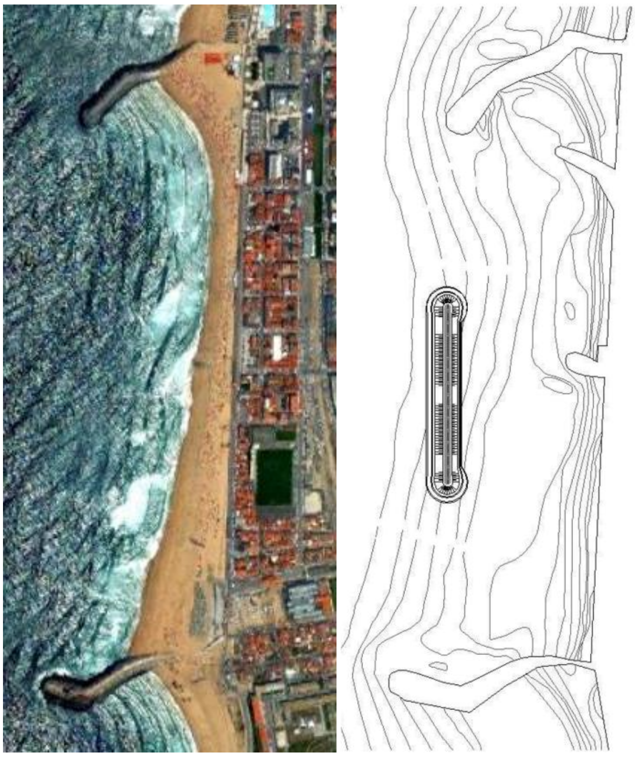

Figure 1: Espinho urban front in July 2010 (left, Google Earth^{TM}). Detached breakwater proposed by Pereira (2008) (right, schematic representation).

In order to mitigate the erosion problem in the central zone between the structures, Pereira (2008) proposed the implantation of a detached breakwater, approximately parallel to the coastline (Figure 1, right). The structure has a length of 360 m and a crest width of 17.7 m. The up-drift armour and the head of the breakwater have slopes of 2:1, and 3:2 on the armour down-drift side. This results in a width of 28 m for the foundation and a total longitudinal development of 421 m. The elevation of the superstructure is +5.0 m CD (Chart Datum), and its foundation is roughly -5.0 m CD.

Numerical Simulations with SMC

Sistema Modelado Costero

The Software Sistema Modelado Costero (SMC) is part of the project *Modelo de Ayuda a la gestión del Litoral*, developed by the group of Coastal and Ocean Engineering at the University of Cantabria, for the Directorate of Coasts of the Spanish Ministry of Environment. It is a graphical user interface of a set of numerical models developed by the project (GIOC, 2003a). The SMC is organized into five core modules, according to the temporal and spatial scales of the processes to be modelled: *Pre-proceso*, *corto plazo*, *medio y largo plazo*, *modelado del terreno* e *tutor*.

The model MOPLA is included in *corto plazo* module and allows to: simulate wave propagation from deep sea to the coast (including the effects of refraction, shoaling, diffraction and dissipation by breaking); estimate the wave induced currents in the surf zone; simulate the beach morphodynamic evolution, calculating the sediment transport due to waves and currents, determining areas of sediment erosion and deposition and assessing beach change, when subjected to those actions (GIOC, 2003b). This model consists of two sets of numerical models, one for regular waves and the other for irregular sea sates. The first set is for application to study the approximate morphodynamics of a coastal stretch and includes: a parabolic model for wave propagation (Oluca-MC), a model for the calculation of wave induced currents in the surf zone (Copla-MC) and a model for beach change (Eros–MC, erosion-accretion).

Numerical Simulations

Numerical simulations were performed with MOPLA in order to evaluate the efficiency of the detached breakwater proposed for the defence of Espinho urban front (Costa, 2009).

The most recent available topo-hydrographic data in digital format for the study site was a 1988 survey geo referenced at Datum 73 (as schematically represented in Figure 1, right). The groins were reproduced assuming a constant crest elevation of +6.0 m CD. From the topo-hydrographic data a digital terrain model was interpolated with an extension of 750 m x 2195 m and a resolution of 5 m in x and y, using a kriging interpolation method. The proposed detached breakwater (Pereira, 2008) was added to the base topo-hydrographic data using the *modelado del terreno* tool from SMC.

The sand particles' size was characterized by a median diameter d_{50}= 0.45 mm, a d_{90}= 0.75 mm and an average standard deviation of 0.12 mm, consistent with characteristic values presented in Silva *et al.* (2009). The value of porosity considered was 0.4 (Soulsby, 1997). Common values for marine sand were used for the specific weight (26.5kN/m^3) and for the angle of repose (32°).

A total of 32 simulations were performed with regular waves, considering two scenarios: one representing the present morphologic situation; the other representing the implantation of the proposed detached breakwater. The 16 simulation conditions resulted from the combination of the base conditions, defined from typical conditions for the northwest coast of Portugal, shown in Table 1.

Table 1: Simulation conditions.

Wave height (H)	Wave period (T)	Wave direction (θ)	Tidal range (z)
2.0 m	12 s	from NW	+ 4.0 m CD
5.0 m	18 s	from W	+ 0.0 m CD

Considered tides are semi-diurnal type with an exceptional higher high water in spring tide of 4.0 m CD. Meteorological tides effects were not considered. Wave conditions were selected from typical average and extreme conditions on the northwest coast of Portugal, as synthesized in Costa *et al*. (2001).

Default values were considered in the formulations of the wave propagation and circulation models. In the wave propagation model, of composite type, dissipation in the turbulent boundary layer and open lateral boundary conditions were considered. In the case of the circulation model, simulations were carried out with 500 s duration, a Chézy roughness of 10 $m^{1/2}/s$ and an eddy viscosity of 10 m^2/s, for a wave period of 18 s, and 6 m^2/s, for a wave period of 12 s. The computational mesh was defined as a function of the wave period, having 10 points per wavelength. In the simulations both the bathymetry and the event in progress, with an admitted duration of 12 hours, evolved in time. All representations of the simulation results are in line with the north.

Results Analysis

The results obtained from the simulations with the wave propagation model (Oluca-MC) show the effect of implantation of the referred detached breakwater. Figure 2 represents the simulated wave fronts superimposed on wave heights. From the analysis of the figure it is possible to observe a shadow zone down-drift the structure, with marked reduction in wave heights. The wave fronts show the change introduced by the breakwater in the refraction pattern of the area between groins and the diffraction pattern around its ends. As it was expected, an increase in wave period promoted a separation between wave fronts. The rise of the tide level also promoted such separation and a translation of wave heights towards the coastline. For the tested conditions, the effect of reduction of wave heights, particularly evident in the breakwater shadow zone, proved to be independent of the wave height, the wave period, the wave direction and the tide level.

The results from the simulations with the circulation model (Copla-MC) and the beach change model (Eros-MC) show the effect of implantation of the detached breakwater. Figure 3 represents the potential sediment transport) (in m^3 per hour, per m of coastline: m^3/h/m.l), since the results for the bathymetry change revealed inconclusive.

The wave direction significantly influenced the results. In the case of waves coming from NW, the currents form an almost steady stream parallel to the coastline, only disturbed at the groins neighbourhood. Whilst in the case of waves coming from W, there is an increase of instabilities in the area between groins.

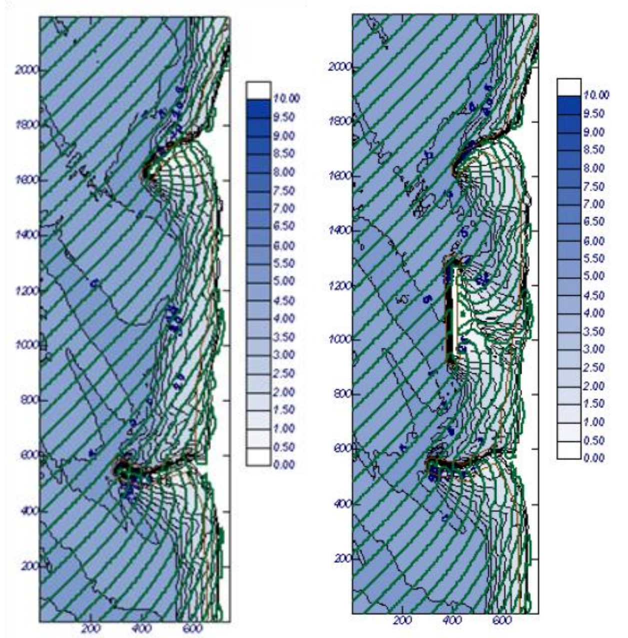

Figure 2: Wave fronts superimposed on wave heights for the present situation (left) and the scenario with the breakwater implantation (right). Simulation conditions: H = 5 m, T = 12 s, θ from NW, z = 4.0 m (Costa, 2009).

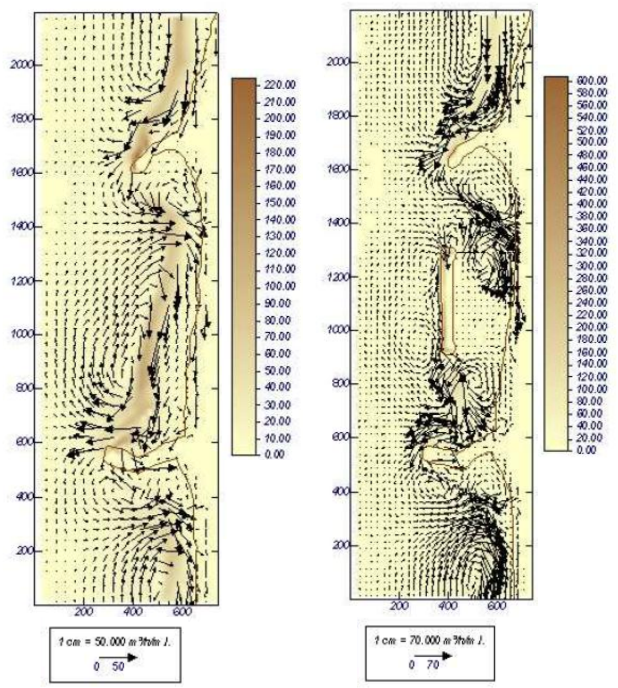

Figure 3: Potential sediment transport for the present situation (left) and the scenario with the breakwater implantation (right). Simulation conditions: H = 5 m, T = 12 s, θ from NW, z = 4.0 m (Costa, 2009).

In the case of a wave coming from NW, the potential sediment transport, northern and southern from the area delimited by the groins, occurs from north to south, preferentially along a corridor with an orientation close to the orientation of the coastline (Figure 3, left).

The wave period practically does not influence the results of circulation. However, although there is no change in the spatial pattern of the potential sediment transport, there is an increase in its intensity with increasing period. An increase in the tide level results in a translation of the currents and the potential sediment transport of greater intensity towards the coastline.

For larger wave heights there are increased current velocities and potential sediment transport. The maximum velocities (between 0.5 m/s and 0.6 m/s) were observed for a wave height of 5 m and a wave direction from NW. For a wave height of 2 m maximum values were in the order of 0.25 m/s. Areas with maximum potential sediment transport occur for a wave height of 5 m, coupled with a wave period of 18 s (of about 150 m^3/h/m.l). For a wave height of 2 m the areas of maximum values were of 50 m^3/h/m.l.

The implantation of the detached breakwater significantly alters the simulation results. The main impact was the displacement of the zone of largest current speed from up-drift the southern groin to down-drift the northern groin, near the most critical zone of the sector between groins in terms of erosion, particularly evident in the simulations with a wave direction from NW (Figure 3). Under this scenario, an increase in the wave height results not only in increased intensity of the circulation currents but also in a change in its distribution pattern, especially for the lowest tide level. For the highest wave height, a tidal level rise traduces into an increase in the potential sediment transport, more significant in that critical area. The highest values of current velocities (about 0.7 m/s) were observed for a wave height of 5 m and a wave direction from NW. For a wave height of 2 m the maximum current velocities were of the order of 0.5 m/s. The wave direction did not significantly affect the potential sediment transport. Maximum values of about 200 m^3/h/m.l occurred for the simulation with a wave height of 5 m and a wave period of 18 s. For a wave height of 2 m these values were of about 80 m^3/h/m.l.

Physical Modelling

Introduction

This study aimed to contribute to the knowledge concerning the effects of detached breakwaters on beach morphology.

Specifically, it aimed to evaluate the morphological effect of different configurations of a detached breakwater parallel to the coastline, when subjected to the action of wave conditions typical of the northwest coast of Portugal. The 3D experimental study was conducted on the premises of the Hydraulics Laboratory of SHRHA-DEC-FEUP. The wave tank occupies an area of 12x28 m^2 and a height of 1.20 m (Figure 4). It is equipped with a multi-element wave generation system, which incorporates dynamic reflection absorption (HR Wallingford). Opposite to the wave generation system, the wave tank has a dissipative beach in order to reduce reflections from its end.

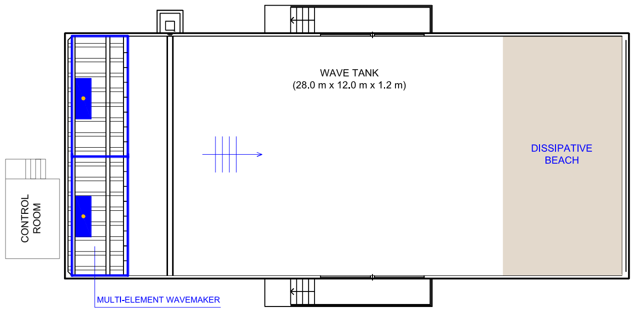

Figure 4: Wave tank of the Hydraulics Laboratory of SHRHA-DEC-FEUP.

Model Definition

The physical model is based on the detached breakwater proposed by Pereira (2008), adapted to the space and the materials available in the laboratory. A geometric scale of 1/40 was adopted. A study of similar characteristics had been conducted shortly before (Silva, 2010). It involved the construction of a structure on the scale 1/37, having been adopted the Hudson formula for the design of the armour blocks weight. It was thus guaranteed that the available materials could be used, representing equivalent solutions of the prototype, for Froude similarity criteria (time scale equal to $1/\sqrt{40}$). Three different configurations (1, 2 and 3) were considered for the structure model (Figure 5), but results will only be presented for configuration 1. Nevertheless, the crest elevation and width were constant in all three cases, with the changes being related to the shape of the breakwater's ends and their slopes. The beach adjacent to the detached structure was made of silica sand with a d_{50}= 0.273 mm.

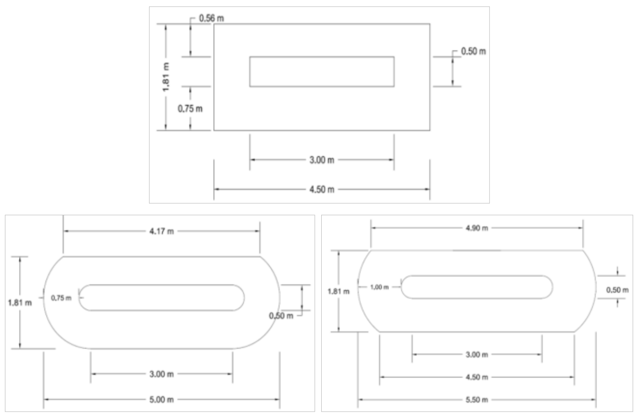

Figure 5: Detached breakwater configurations: 1 (top), 2 (bottom left) and 3 (bottom right) (China, 2011).

The cross-section of the three models was the same (Figure 6). The core of the structure was completed with permeable geotextile bags filled with sand of various sizes.

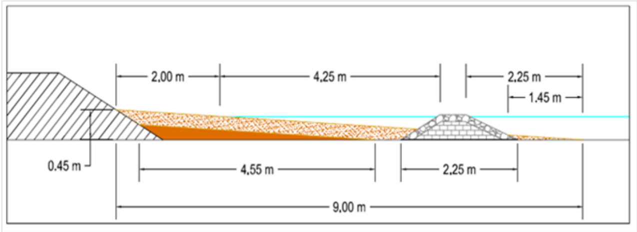

Figure 6: Cross-shore profile of the model (China, 2011).

The first sublayer was materialized with gravel of various sizes, according to the weight of the armour layer blocks from the prototype, between 110 and 150 kN.

Experimental Set-up and Experimental Procedure

The constructed physical models were submitted to the action of irregular sea states for the selected representative typical conditions in the northwest coast of Portugal (peak wave period, T_p= 10 s, significant wave heights, H_s= 3.0 m and H_s= 5.0 m) defined through a Jonswap spectrum, in the wave generation system. These values were consistent with the wave generation system limits and the water depth, allowing at least one wavelength between the structures ends and the wave tank wall.

Seven experimental tests were conducted (Table 2), with an approximate duration of 13/14 hours: 8 hours of effective wave action (more than 2 days in the prototype) and 4/5 hours for bottom surveying. However, according to Chen & Kuo (1994), for sea states characterized by T_p= 10 s, the largest and most rapid morphological changes would occur during the first 8.78 hours, but a state of equilibrium would only be reached after 26.35 hours.

Table 2: Experimental tests.

Test	Configuration	Wave height	Water depth
1	1	3.0 m	0.0 m
2	1	5.0 m	0.0 m
3	2	3.0 m	0.0 m
4	2	5.0 m	0.0 m
5	3	3.0 m	0.0 m
6	3	5.0 m	0.0 m
7	3	3.0 m	4.0 m

Due to the model symmetry in relation to the principal longitudinal direction of the wave tank and to the fact that the incident waves were orthogonal to the structure, morphological changes were also assumed to be symmetric. Thus, surveys were only carried out on one half of the beach. A touch sensitive bed profiler (HR Wallingford) was used for the measurement of five cross-sections spaced 1 m (Figure 8). For each profile (3900 mm in length) the bottom height was registered in 70 equally spaced points.

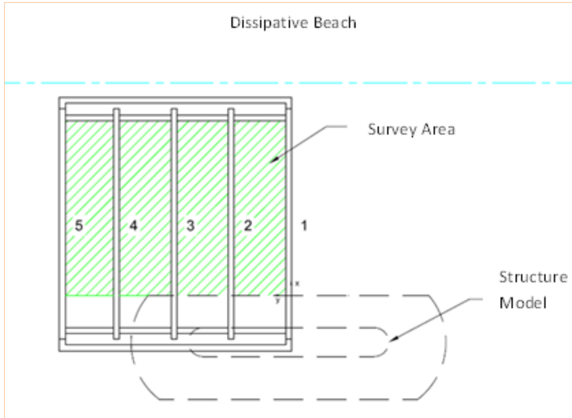

Figure 8: Beach profiles in the survey area (China, 2011).

Results Analysis

The influence of the incident significant wave height in the sediments distribution pattern behind the structure was evaluated by comparing the results of test 1 and test 2. Figure 9 shows the interpolation of the registered bottom variation in the five profiles.

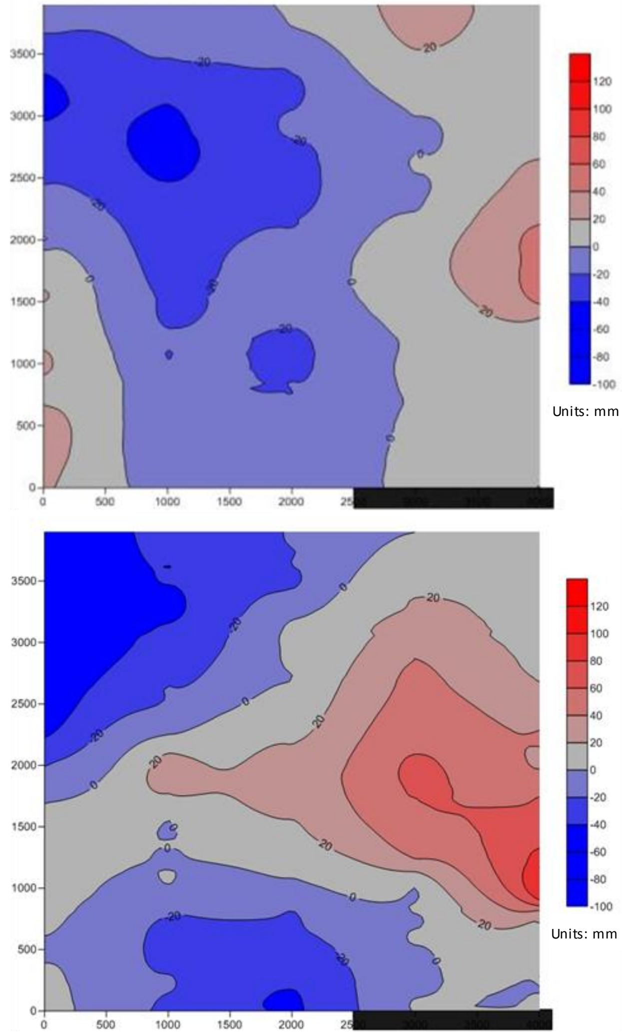

Figure 9: Bottom change relative to the initial beach during test 1 (top) and test 2 (bottom) (China, 2011).

A first analysis of Figure 9 allows realize that the distribution of the accumulation/erosion areas is similar in both tests. However, a lateral extension of the main area of accumulation, affecting profiles 3 and 4, occurs during test 2 (higher incident significant wave height). In both tests, negative bottom changes, with considerable amounts, occur close to the ends of the structure. A careful analysis shows that the sand swept of erosion zones, is the same feeding areas of accumulation.

Figure 10 shows profile 1 evolution during test 1 and test 2.

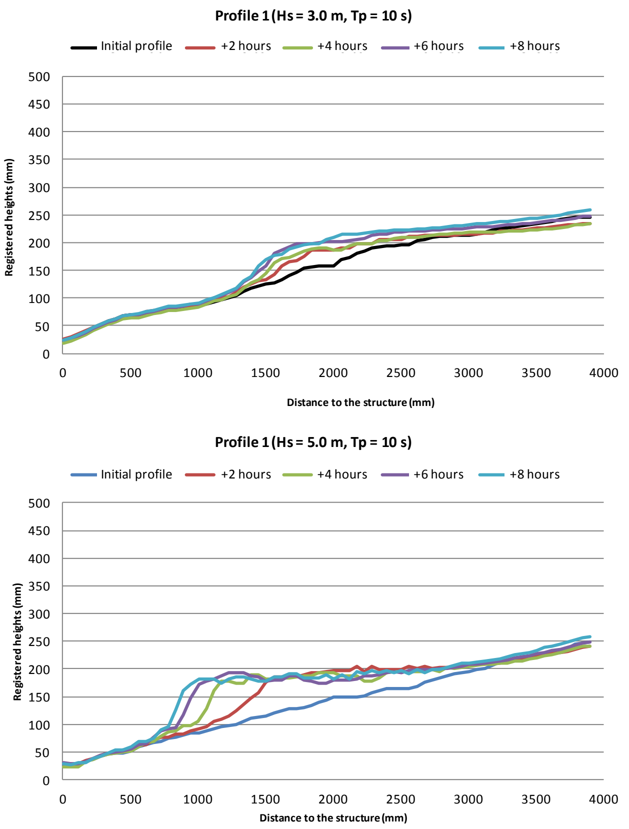

Figure 10: Profile 1 evolution during test 1 (top) and test 2 (bottom) (China, 2011).

From the figure analysis, for the same period of time, profile's evolution during test 2 (more energetic wave conditions) is more pronounced than during test 1, although a slight attenuation may be noted as time progresses. During test 1 an equilibrium state seems to be achieved, however, this state was not observed during test 2.

From the presented analysis, which is also consistent when the results from test 3-test 4 and test 5-test 6 are compared, we conclude that the profile response is related to the energy of the incident sea state, which is as intense and prolonged in time as the higher the sea state energy.

Configuration 1 proved to be the one providing a more abrupt change in normal wave propagation, leading to significantly higher erosion near the ends of the breakwater (China, 2011).

Conclusions

The numerical simulations showed that, for the conditions tested, despite the protection offered by the detached breakwater to Espinho urban front, complications could arise due to instabilities introduced in the currents field and, consequently, in the transport capacity. The breakwater implantation caused a northward migration of the maximum potential sediment transport, precisely to the most critical area of the sector in terms of erosion. Thus, these results raise questions about the efficiency of the proposed breakwater, suggesting the need to optimize its configuration.

The experimental results showed that the configuration of the ends of the breakwater could also affect its efficiency.

In continuation of this study, it would be interesting to explore the combined use of the set of numerical models incorporated in SMC, for simulations with irregular sea states, and physical models to test different configurations and implantation location of detached breakwaters, for the evaluation of their efficiency as coastal defence structures.

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