Modelling the morphodynamics in the vicinity of a submerged detached breakwater

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Abstract

The importance that coastal zones assume in Portugal implies a necessity for adequate responses to erosion-associated risks. One example is the coastal stretch located between the Mondego and Lis rivers' inlets (study zone), which has been a frequent target of protection measures, such as the construction of groins. This kind of solution drove to the artificialization of that area, resulting in significant changes in the coastal landscape. A possible alternative is a submerged detached breakwater, which provides beach protection and enhance local surfing conditions, without any loss of beach amenity or negative aesthetics impact. Thus, in this study the morphodynamics resultant of the wave - breakwater - bottom interaction in the active zone located in the vicinity of this kind of structure was analysed by means of two numerical models: a two dimensional, depth-averaged (2DH), Delft3D, and one-line, LITLINE. These were applied considering typical hydrodynamic forcing conditions (mean and most frequent waves) and morpho-sedimentologic conditions of the site. Using Delft3D, the sensitivity of the breakwater's parameters to the morphological response of the beach was analysed. The coastline evolution results were compared with LITLINE's predictions. It was verified that Delft3D reproduces the circulation patterns in the structure's vicinity, and between the structure and the coastline which influence its evolution. On the contrary, the LITLINE's model simplifications do not enable a representation of the physical phenomena which dominate the breakwater's vicinity. This analysis will provide support to projects for the implementation of this kind of structure in the studied area.
Keywords: Numerical modelling, Delft3D, Submerged breakwaters, Coastal processes, Erosion, Figueira da Foz.

1. INTRODUCTION

Portugal has a long coastal extension and its historical journey was always associated to the sea, estimating that 75% of the portuguese population nowadays lives in the coastal zones and this value is expected to increase in the next years. The main problem these areas have been facing in the last decades is the increasing number of conflicts between their development and erosion phenomena.

The long-term erosion phenomena observed in large extensions of the portuguese coast is due in part to a deficit in sediment supply to the coast provoked by anthropogenic actions and aggravated by climate change, specifically the acceleration of sea level rise (Antunes and Taborda, 2009). Additionally, the portuguese coast is one of the most energetic in Europe, with very high sediment transport, high seasonal variability and occurrence of very energetic storms. These problems have particular impact in storm occasions, when overwashing and inundation in maritime fronts of population settlements occur, and there is the need to defend people and infrastructures.

The importance that coastal zones assume strategically in environmental, economical and social terms in Portugal implies a need to tackle the erosion-associated risks. The recommended approach for the present and future of the coastal zone is that the human occupation in these areas and the activities that they support should respect and adapt to the present and future coastal dynamics (Santos *et al.*., 2017). There are three types of adaptation strategies that can be considered: protection, relocation and accommodation. The first strategy, protection, has been the lead approach to coastal risks. It consists in maintaining or advancing the coastline through artificial beach nourishment, construction of artificial dunes or of hard structures such as groynes, detached breakwaters and seawalls.

The conventional stabilization structures, such as groynes and seawalls, are the most common. These kinds of hard structures have led to a severe artificialization of coastal zones, resulting in significant changes in the coastal landscapes and in the environment. Therefore, this kind of protection approaches are becoming increasingly unpopular due to their adverse impact on beach amenity and aesthetic considerations. In contrast, submerged structures are increasing in popularity due to their multi-functional design which provides the dual benefits of beach protection and enhancement of local surfing conditions, without any loss of beach amenity or negative aesthetic impact. An example of such a multi-fuctional design is the artificial surfing reef at the Gold Coast in Australia (Black and Mead, 2001). In Portugal, there is an example of emergent artificial reefs in Aguda beach and Castelo de Neiva, nonetheless these breakwaters are founded in natural rock formations, which makes it difficult to model their behaviour.

Contrary to emerged structures, fully submerged structures have only rarely been adopted for beach protection, for this reason their efficacy remains largely unknown. The existing literature about submerged breakwaters (SBWs) is limited, mainly focused in empirical relations and field experiences. Ranasinghe and Turner (2006) presents a review of existent SBWs, showing that in the majority of cases, erosion in their lee occurs. However, the study of Black and Andrews (2001) reveals that natural submerged reefs, which are similar to SBWs, are frequently associated with shoreline salients. Furthermore, shoreline erosion is almost never reported in the lee of emergent structures. This indicates that the scarce number of existing studies is inconsistent.

These considerations mean that, prior to the wider adoption of SBWs for beach protection, further investigation of the physical processes governing shoreline response to these structures is necessary. Improving the knowledge of the relevant physical processes can be done via simulation methods (numerical or experimental) and *in situ* monitorization (Ranasinghe and Turner, 2006; Turner *et al.*., 2001; Tomasicchio, 1996). The present report uses the first class of methods to study the morphodynamics around a SBW located between the Mondego and Lis rivers' inlets (study zone) by means of two numerical models: a two dimensional, depth-averaged (2DH), Delft3D (Deltares, 2011a,b), and one-line, LITLINE (DHI, 2016).

2. CASE STUDY

This study focuses in a coastal stretch located in central-west part of Portugal, being limited by the Mondego and Lis rivers' inlets, at north and south, respectively (Figure 1).

The continuous beach-dune system constitutes the coastal stretch, which is approximately rectilinear with an extension of 32 km and mean orientation equal to 19.6°N (Oliveira and Brito, 2015). It is characterized by the existence of natural sandy beach in all of its extension, interrupted by a rocky headland in Pedrógão. Furthermore, the bathymetric lines in the study stretch are parallel to each other, presenting significant regularity. The physiographic unit in analysis includes the maritime frontages of the urban centers of Gala-Cova, Costa de Lavos, Leirosa and Pedrogão.

The considered coastal stretch has been strongly influenced by anthropic interventions of different kinds since mid 20th century (Oliveira and Brito, 2015), in order to tackle shortages and undesired sediment accumulation and to model the coastal profile. Due to the induced sediment capture by Figueira da Foz's harbour jetties, various coastline stabilization and population protection structures were built, leading to the massive construction of groynes and seawalls along the study area. The study stretch is characterized by being permanently exposed to a wave climate regime that leads to an intense sediment transport, south-oriented.

3. DATA AND METHODS

3.1. Hydrodynamic forcing conditions

In order to set up the models it is necessary to define the hydrodynamic characteristics that are representative of the case study. Based on the statistical analysis of a validated hindcast wave parameters time series for the period 1952 – 2010 by Oliveira (2016b), a wave climate highly energetic and with high seasonal variations was identified, with characteristics mean wave direction (Dir) of 299.5° (10° towards NW with respect to the shoreline normal in the study stretch), significant wave height (H_s) 2.15 m and peak period (T_p) 11.5 s. In terms of the most frequent spectral wave parameters, based on the same study, the following values were adopted: H_s = 1.25 m, T_p = 9 s and Dir = 305°. At the offshore boundaries it was prescribed a stationary wave spectrum and the mean sea level (MSL) 2 m above the zero of the nautical chart datum (CD).

3.2. Topo-hydrography and sedimentology

The selection of the representative cross-shore beach profile was based on the morpho-sedimentologic characterization of the study zone done by Oliveira and Brito (2015). The initial morphology conditions of the study zone were simplified by assuming simplified bottoms (sediments and beach profile) and alongshore uniformity, in order to limit the complexity of the computed coastal processes. The resulting beach profile obtained by Oliveira (2016a) has three slopes for each zone (Figure 2):

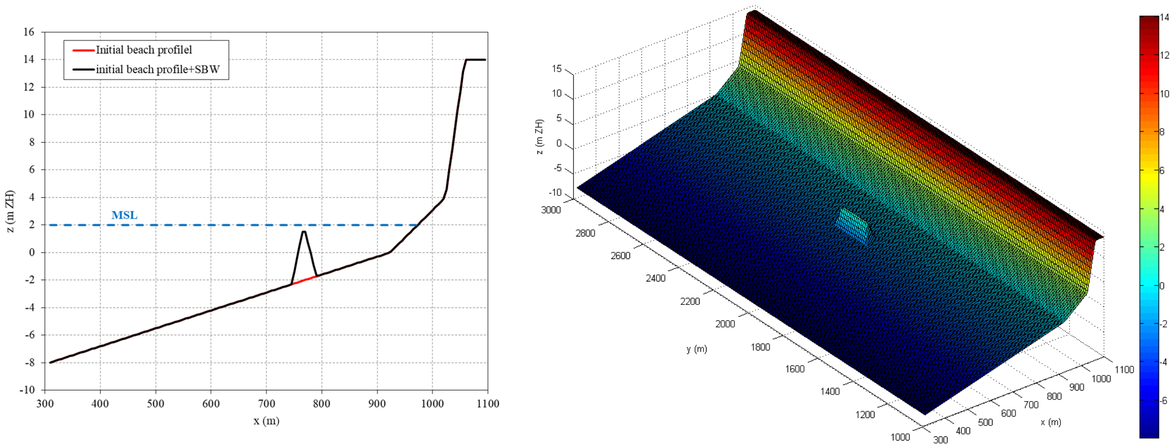
- frontal dune face – 1:3.5 (located between 4 m above CD and the frontal dune crest 14 m above CD);
- beach face – 1:25 (located between CD and 4 m above CD);
- submerged profile – 1:77 (located between 12 m below CD and CD).

The representative sediment median diameter (D_{50}) was considered uniform along the cross-shore profile and equal to 0.30 mm.

3.3. Methods

Herein the setup of the two considered process-based numerical models, Delft3D and LITLINE is described. Both models were calibrated according to Oliveira *et al.*. (2018) so that the longitudinal sediment for the mean wave transport would attain 1 800 000 m^3/year, which

Figure 1: Location of the studied coastal stretch, comprised between the Mondego and Lis rivers inlets, and aerial view of the main adjacent structures and urban centers. Adapted from http://portugalfotografiaaerea.blogspot.com (consulted in September 2018).



(a) (b)

Figure 2: Initial topo-hydrography: (a) profile and (b) 3D perspective obtained from Delft3D.

is a known value for the portuguese coast (Vicente and Pereira, 1986). Specifically, for the Delft3D model the values of the wave-related transport factor for suspended and bed-load sediments were defined equal to 0.1, and in the LITLINE model the bottom roughness was defined equal to 0.00004.

The computational domain of the Delft3D model includes two uniform cartesian grids: FLOW and WAVE grids. The FLOW grid corresponds to the Delft3D-FLOW module, which covers a larger domain than the study zone, insuring that the boundaries do not influence the results. The FLOW grid is two dimensional (depth-averaged) and covers an area of 2000×790 m^2 in the alongshore and cross-shore directions, respectively. A larger grid is used for the waves solver, WAVE grid (corresponds to the Delft3D-WAVE module), which covers an area of 4000×1100 m^2 in the alongshore and cross-shore directions, respectively. The WAVE grid overlays the FLOW grid to avoid boundary problems. The grid's cell spacial resolution is uniform: $\Delta y = \Delta x = 5$, alongshore and cross-shore directions respectively. To include the SBW, the bathymetry was locally changed in the FLOW module based on the design parameters such as slope, structure length, crest submergence level and distance to the shoreline. The breakwater slope remained constant in all the tests made, considering a length equal to 20 m for the cross-shore and alongshore profiles (Figure 2(a)).

After several sensitivity tests, the SBW was defined as structure, rough bottom, in the FLOW module by including a non erosive sediment layer and by the differences in bottom roughness. To include a non-erosive SBW, an initial sediment layer of 0 m was formulated locally, while for the surrounding bathymetry the bottom consisted in a sediment layer of 5 m (enabling morphological changes). The differences in bottom roughness between a sandy bottom and the SBW were accounted by using a spatial varying Chézy coefficient (C): for the SBW crest C = 20 $m^{1/2}s^{-1}$ and for the sandy bottom C = 65 $m^{1/2}s^{-1}$. In the WAVE module, the SBW was defined as an obstacle, affecting the wave propagation.

The Delft3D-FLOW module was coupled to the SWAN wave module, in order to take into account the wave-induced effects on hydrodynamics and morphology. The coupling time, after which these modules exchange information, was set equal to 10 min.

In regard to the boundary conditions, north and south boundaries were forced with water level gradient boundaries (Neumann) and the west offshore boundary was forced with an open water level boundary.

In order to enable numerical simulations for longer time scales, the morphological acceleration factor (morfac) approach was used. The simulation period was defined for one day, but by using a morfac of 30 the tests were made for a period of 30 days.

The computational domain of the LITLINE model includes an initial straight coastline that was considered equal to the MSL isoline, with an extension of 4000 m. The depth of the offshore limit of the active zone of the representative cross-shore beach profile (Figure 2(a)) was defined equal to -3.354 m CD, corresponding to an active length of 310 m. The top of the dune was set at 14 m CD and the beach berm at 4 m CD, which resulted in an active height of 7.354 m. The considered spatial resolution was the same, $\Delta y = \Delta x = 5$, as well as the lateral boundaries which were forced with Neumann boundary conditions.

Several tests were made in order to predict the morphological evolution in the vicinity of the SBW during 30 days using Delft3D model summarized in Table 1. In Figure 3 the design parameters of the SBW are represented. The test H1 considers an emerged breakwater, above MSL, for the purpose of comparing the Delft3D model outcome with LITLINE's, since the latter doesn't allow testing breakwaters below MSL.

4. RESULTS AND DISCUSSION

4.1. Reference case

The Delft3D model's outcome in predicting the morphological evolution in the vicinity of the SBW during 30 days of local mean wave action is presented in Fig-

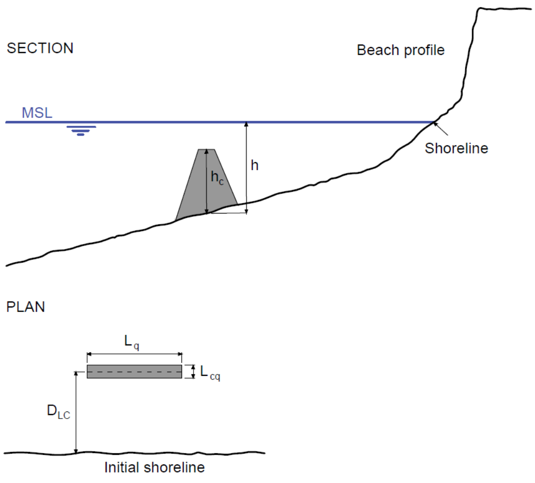


Figure 3: Schematic diagram showing key design parameters for a SBW: structure length (L_q), distance from shoreline to structure (D_{LC}), crest width (L_{cq}), crest height (h_c) and depth to sea floor at structure (h).

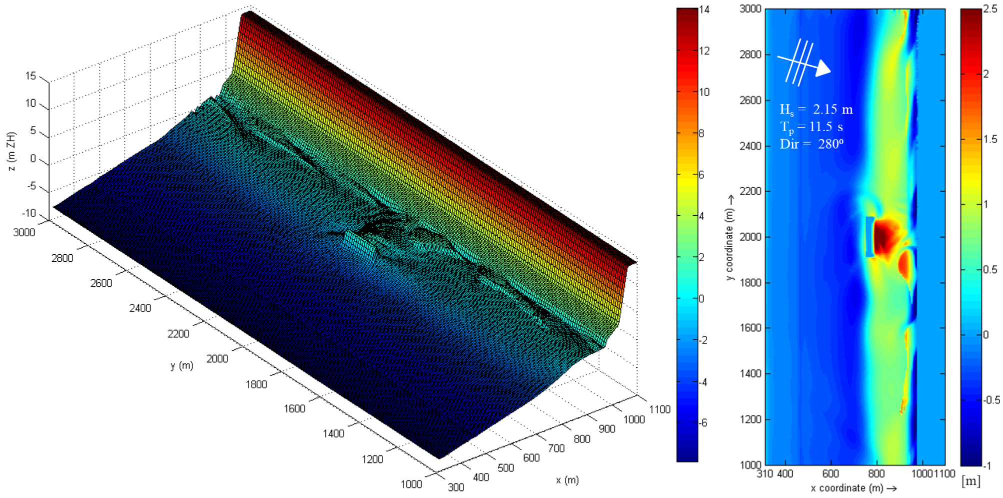
Table 1: Test conditions. Shadowed cells indicate variations with respect to the reference case.

Tests	Name	L_q [m]	L_{cq} [m]	D_{LC} [m]	h [m]	h_c [m]	H_s [m]	T_p [s]	Dir [°]
Reference	R	150	10	204	4	3.5	2.15	11.5	280
Most frequent wave	F	150	10	204	4	3.5	1.25	9	285.5
Crest height h_c	H1	150	10	204	4	4.5	2.15	11.5	280
	H2	150	10	204	4	3.0	2.15	11.5	280
	H3	150	10	204	4	2.5	2.15	11.5	280
	H4	150	10	204	4	2.0	2.15	11.5	280
Distance to shoreline D_{LC}	D1	150	10	320	5.5	5.0	2.15	11.5	280
	D2	150	10	400	6.5	6.0	2.15	11.5	280
	D3	150	10	500	7.8	7.3	2.15	11.5	280
Structure length L_q	L1	300	10	204	4	3.5	2.15	11.5	280
	L2	400	10	204	4	3.5	2.15	11.5	280
	L3	500	10	204	4	3.5	2.15	11.5	280

ure 4. The stationary wave boundary conditions produced:

- the formation of submerged oblique bars, quasi-rhythmic bottom features (rip-like). The development of these bars is typically associated to incident waves with angles smaller than 30° with respect to the shore normal, which is the case of the study stretch. The growth of these bedforms can be observed in nature, although their cause is unclear – Giardino *et al.*. (2010) points out that it could be related to natural instabilities or model inaccuracies;

- the advance of the beach face in the lee zone of the SBW due to the reduced wave energy and thereby the sediment carrying capacity of the waves alongshore. The sheltering effect of the SBW enables tombolo formation (in this study it was considered that a tombolo was formed in the lee of the SBW



(a) (b)

Figure 4: Test case R: (a) numerical morphology after 30 days and (b) numerical morphological evolution during 30 days (results of Delft3D model).

when sediment accumulation exceeds CD, approximately the low water level);

- sediment accumulation in the lee of the SBW is symmetrical. The maximum sediment accumulation values are also reached in this zone (>2.5 m). Close to the shoreline an asymmetry of the accumulation pattern also occurs, since the mean wave action overlays the formation of the submerged bars, being more significant south of the SBW;

- erosion is observed between the submerged bars formation, though it is not caused by the SBW.

The filling differences in the lee zone of the SBW are presented in Figure 5, confirming that the central profile (Figure 5(b)) is the one with the maximum sediment accumulation (2.98 m of seabed elevation). At the end of the 30 days, erosion is observed from the initial depth -7.84 m CD up to -2.70 m CD, meaning that the sand is carried from greater depths and deposited close to SBW (sea side), resulting in 0.80 m of seabed elevation. The cross-shore profiles 50 m south and north of the SBW (Figures 5(a) and 5(c) respectively) show less seabed elevation in the lee zone of the SBW and also erosion in the beach face due to development of submerged bars. In addition, south of the SBW the sediment accumulation in the lee zone is higher due to obliquity of the incident waves. In the first 10 days the adaptation rate is higher, and then it starts to stabilize.

The significant wave height is also represented in Figure 5, showing that for the central profile, after 30 days the wave breaking occurs for H_s = 2.3 m and at depth of 0.66 m.

The total transport is presented in Figure 6(a). It is evident that the longshore transport prevails with a direction from north to south in the active beach zone. The permanent action of the local mean wave during one year creates a littoral drift of 956 013 m^3/year (value calculated for y = 2000 m), as expected the presence of the SBW reduced the known value for the stretch study (1 800 000 m^3/year).

The 2DH circulation currents and induced sediment fluxes due to alongshore gradients in wave setup can be identified in Figure 6(b). The onshore flow over the SBW diverges in the lee of the structure resulting in an asymmetrical circulation pattern: the development of a seaward return flow around the north end of the SBW and a circulation cell in the lee of the structure which converges in the south end of the SBW (the longshore current is enhanced due to the superposition of the unidirectional longshore currents, caused by obliquely incident waves, on the nearshore circulation cell).

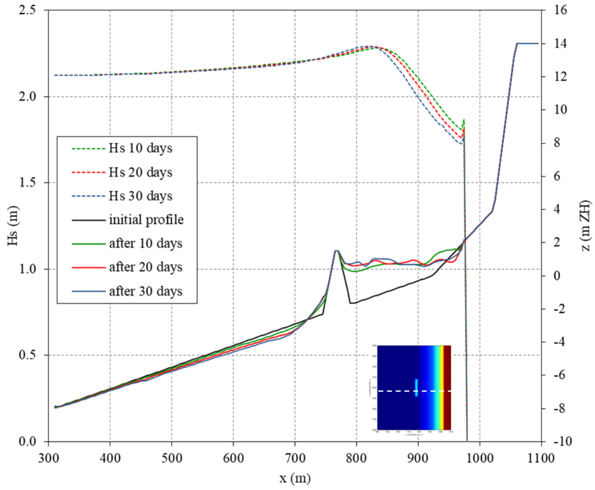
4.2. Influence of design parameters

4.2.1 Crest height (h_c)

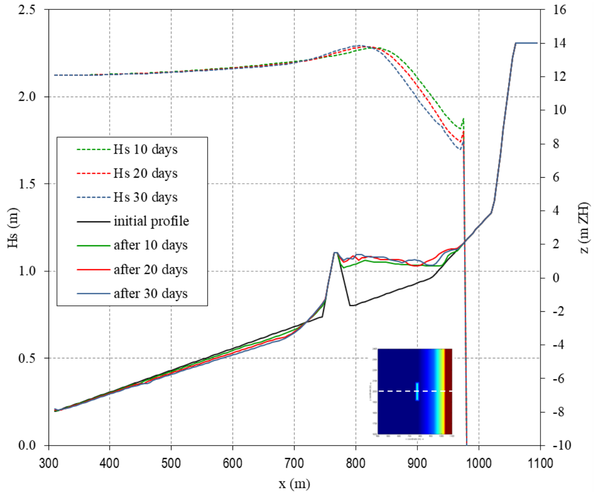
Several tests were made in order to evaluate the effect of the crest height in the vicinity of the structure (Table 1), leading to the following conclusions:

- test case H1 (Figure 7(a)), which corresponds to an emerged breakwater, 0.5 m above MSL, has the highest seabed elevation in comparison with the other tests (>2.5 m). This was expected because the sheltering effect of the structure is higher. The accumulation patterns from test H1 and R are very similar;

- the model outcome produces bigger differences on the accumulation patterns when the breakwater is submerged, as presented in Figures 7(b), 7(c) and 7(d), where the difference between crest height is 0.5 m;



(a)



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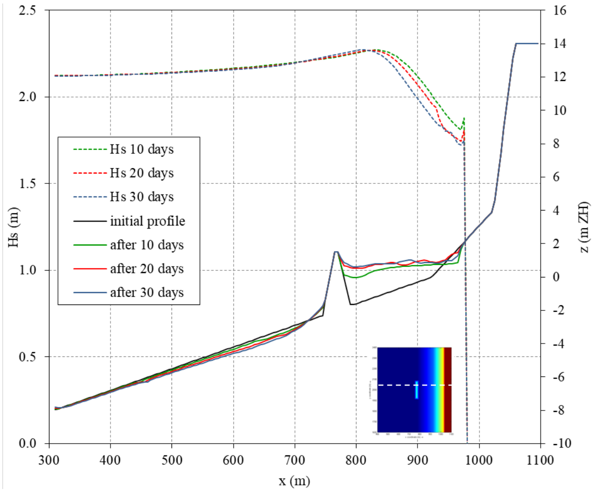
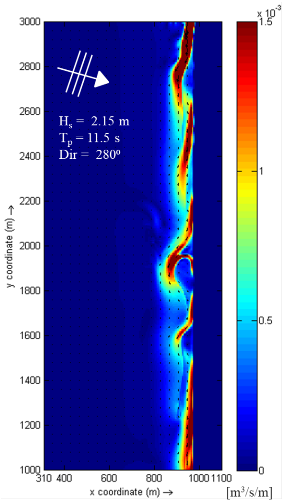
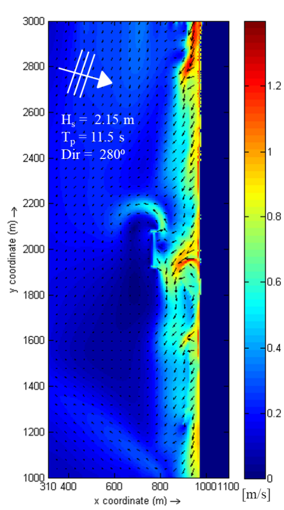


(c)

Figure 5: Test case R: simulated profile evolution and corresponding H_s for (a) y = 1950 m, (b) y = 2000 m and (c) y = 2050 m (results of Delft3D model).



(a)



(b)

Figure 6: Test case R: (a) total transport (suspended and bed load) and (b) depth averaged velocity after 30 days (results of Delft3D model)

- an increase of the submergence level (which means lower crest heights) results in a decrease of the seabed profile elevation in the lee of the breakwater. Despite that, erosion is observed around the tips of the structure, specifically for test cases H3 and H4 with submergence levels of 1.5 m and 2.0 m below MSL, respectively. This local erosion is associated with the 2DH circulation patterns, i.e., the seaward return flow around the tips of the structure;
- the cross-shore central profile presented in Figure 8 illustrates that the maximum seabed elevation for test case H1 is 3.5 m, H2 is 2 m, H3 is 1.18 m and H4 is 0.93 m. For submergence levels below 1.5 m, the beach profile starts to stabilize.

4.2.2 Distance to shoreline (D_{LC})

The effect of the distance from the SBW to the shoreline was also evaluated (Table 1) producing the following outcome:

- tombolo formation is observed for test case D1 (Figure 9(a)), just like test R, although the sediment accumulation pattern is different. In test case D1, where the SBW is 320 m from the shoreline, the sediment accumulation extends far from the ends of the SBW, nevertheless this accumulation is more evident in the south end of the structure. In addition, the maximum accumulation values are observed in the lee of the SBW from test D1 (>2 m). This outcome is counterintuitive, because it would be expected that for longer distances to the shoreline the sediment accumulation should decrease. This phenomenon can be explained by

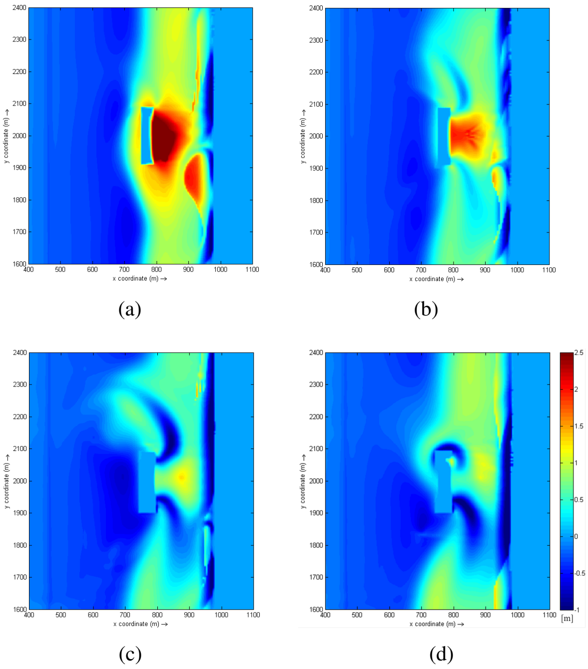

(a) (b) (c) (d)

Figure 7: Numerical morphological evolution during 30 days for test cases (a) H1, (b) H2, (c) H3 and (d) H4 (results of Delft3D model).

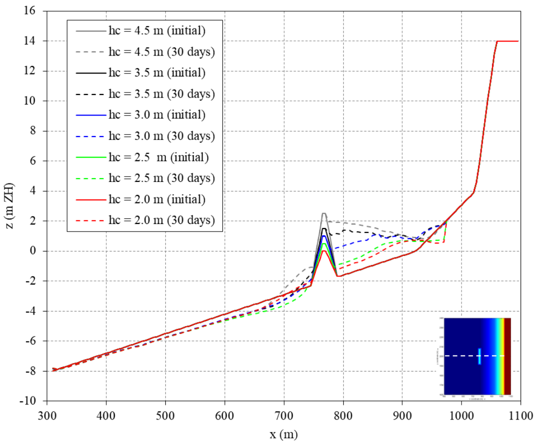


Figure 8: Test cases R, H1, H2, H3 and H4: simulated profile evolution after 30 days for y = 2000 m (results of Delft3D model).

the stationary wave conditions, as in nature the incident waves direction varies as well as the wave energy which would lead to different accumulation patterns;

- the active beach zone reduces with the increase of distance to the shoreline;
- for test cases D2 and D3 (Figures 9(b) and 9(c), respectively) the model outcome predicts that for higher distances from the SBW to the shoreline the influence of the structure in the surroundings decreases, as well as the sheltering effect (less sediments are deposited and retained in the lee zone of the SBW). The asymmetrical accumulation pattern is also present in both tests;
- the effects of increasing the distance from the SBW to the shoreline are also presented in the cross-shore profile in Figure 10. The advance of the beach face in the lee side of the SBW reached the maximum values of 3.39 m, 2.85 m, 1.92 m of seabed elevation at the end of the 30 days for test cases D1, D2 and D3 respectively.

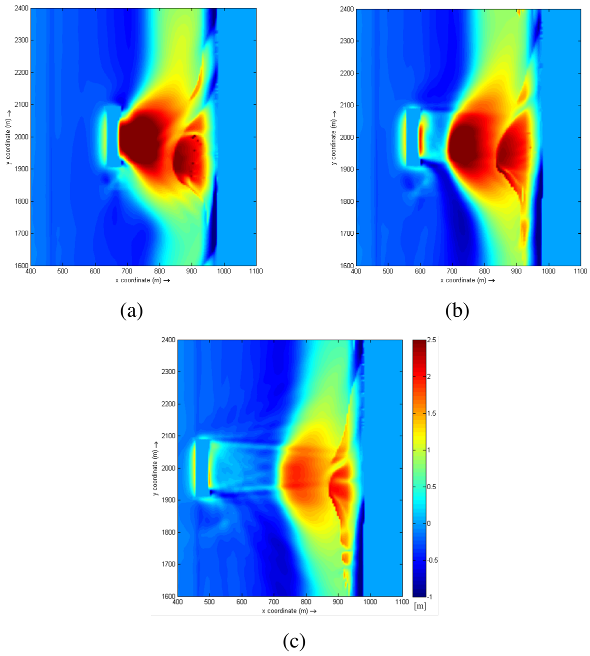

(a) (b) (c)

Figure 9: Numerical morphological evolution during 30 days for test cases (a) D1, (b) D2 and (c) D3 (results of Delft3D model).

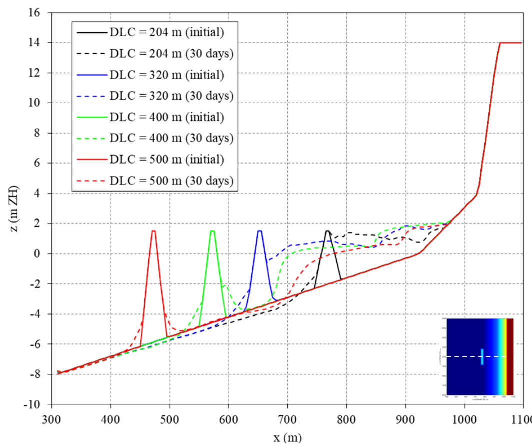
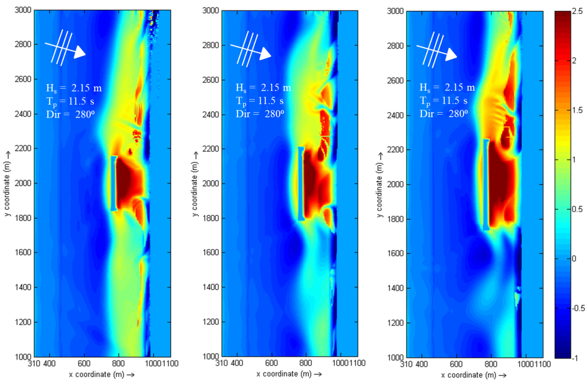


Figure 10: Test cases R, D1, D2 and D3: simulated profile evolution after 30 days for y = 2000 m (results of Delft3D model).

4.2.3 Structure length (L_q)

The last tested design parameter was the SBW length (Table 1). The model predicted that the induced sediment accumulation in the lee of the SBW is higher with structure length increase (Figures 11(a), 11(b) and 11(c)), beginning to function like a T-shaped groyne. The sediment accumulation starts to advance to north, specially in test L3, blocking the sediment flux passage to south. The blocking effect also induces erosion south of the SBW, more significant in tests L2 and L3.



(a) (b) (c)

Figure 11: Numerical morphological evolution during 30 days for test cases (a) L1, (b) L2 and (c) L3 (results of Delft3D model).

The central cross-shore profile is presented in Figure 12. For all three tests the maximum level of sediment accumulation is reached, with maximum seabed elevation of 1.3 m. Close to the SBW in the sea side, the sediment accumulation is also higher than the reference case, test R.

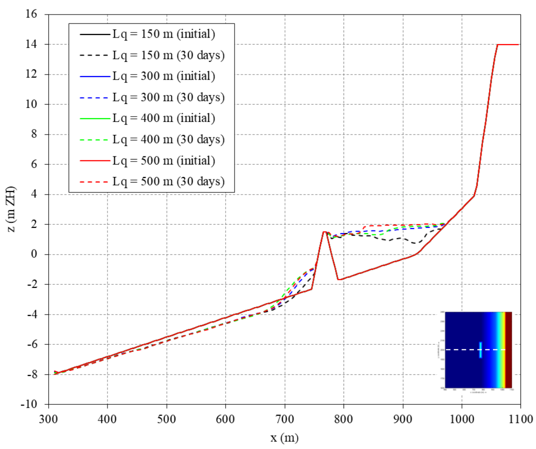


Figure 12: Test cases R, L1, L2 and L3: simulated profile evolution after 30 days for y = 2000 m (results of Delft3D model).

4.3. Most frequent wave effect

Besides the tests to the effect of the design parameters, the morphological evolution in the vicinity of the SBW was also tested for a less erosive wave, like the most frequent wave (Table 1). In comparison to the test case R, where the local mean wave was tested, the model produced the following differences:

- the formation of submerged bars was attenuated;
- the sheltering effect of the SBW is reduced in the lee zone, since the most frequent wave has less transport capacity. In test case R there was the combination of two effects: the erosive wave effect (erosion of the beach face and transport to the offshore) and the SBW induced effects on the shoreline. In this case, test F, there is only the sheltering effect induced by the SBW presence, which isn't enough for tombolo formation. The maximum seabed elevation reached the value of 1.2 m in the lee of the SBW;
- erosion south to SBW is observed and the beach active zone is reduced.

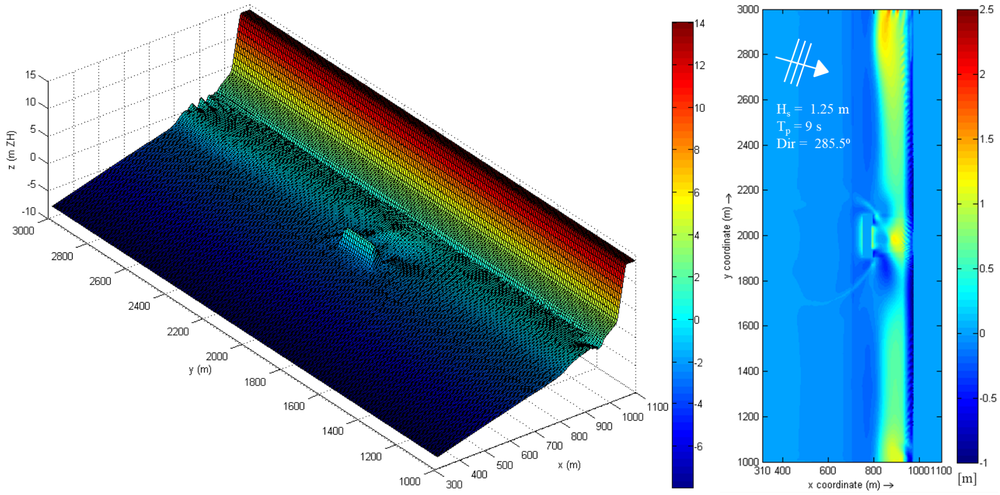
The most frequent wave is less erosive, thereby the permanent action of this forcing wave during one year drives a littoral drift of 17 817 m^3/year for the study stretch, which is in agreement with previous knowledge since the mean wave has a higher transport capacity than the most frequent spectral wave parameters.

4.4. Comparison between Delft3D and LITLINE models

The LITLINE model outcome in predicting the MSL isoline evolution in the vicinity of the SBW is presented in Figure 14. Due to the obliquely wave attack, the MSL isoline evolution is asymmetrical, advancing at north and retreating at south of the structure. After 30 days, salient formation is predicted, registering a maximum advance of 18 m in the lee of the SBW, and a maximum retreat of 35 m at south (y = 1936 m).

The comparison of the outcome of the models is presented in Figure 15. This comparison has been made for an emerged detached breakwater (test H1) in order to evaluate the importance of coastal processes as well as the models' performance. The MSL isoline predicted by Delft3D model remains pratically constant after 30 days, as opposed to the LITLINE model, which predicts a significant advancement and retreat, respectively north and south of the SBW.

The results show the differences in the modelling capacities of both models. The LITLINE model is simpler, and usually used in medium-scaled spacial applications (in the order of kilometers), and in medium-long term (in the order of years to decades), was already applied to the study zone (Oliveira, 2016a,b). At the cost of process simplification, this model presents considerably reduced computational costs, and thus it is usually



(a) (b)

Figure 13: Test case F: (a) numerical morphology after 30 days and (b) numerical morphological evolution during 30 days (results of Delft3D model).

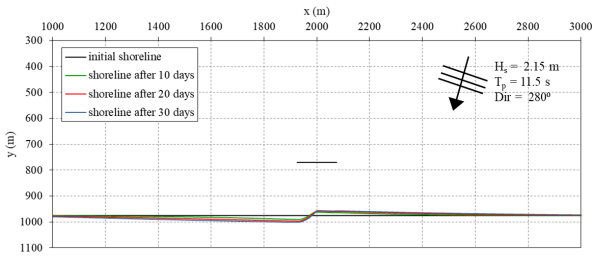


Figure 14: Simulated shoreline evolution in the vicinity of an emerged detached breakwater subjected to a stationary wave (most frequent wave): initial shoreline, after 10, 20 and 30 days (results of LITLINE model).

applied to much larger time and spacial scales than the complex Delft3D model. However, when used to predict the impact of a SBW in the surroundings, it is unable to account for some alterations. The shelter effect enabled by the breakwater induces large variability in sediment fluxes and hence in the cross-shore beach profile in the lee of the structure, i.e., the governing morphodynamic processes are predominantly 2DH. This means that the application of the LITLINE model is unfit and the Delft3D model is more capable of simulating the coastline alterations induced by the presence of this kind of structure. This is because it allows the reproduction of circulation patterns that occur in the vicinity of the structure and between the structure and the coastline.

Therefore, Delft3D is a more complete process-based model, which solves wave propagation, sediments fluxes, sediment transport in the longshore and cross-shore components and the morphological alterations in the same computation step and in both directions of the horizontal plane. This allows for a better representation of nature, though at high computational costs and only applicable to limited spatial and time scales.

5. CONCLUSIONS AND FUTURE WORK

The process-based morphodynamic numerical models Delft3D was applied for the case of morphological evolution of an alongshore uniform bathymetry and uniform grain size submitted to a stationary oblique wave spectrum in the presence of a detached breakwater during 30 days.

Considering simulations from the numerical Delft3D model, it is observed that the mean wave action produced accumulation of sediments in the lee of the structure, due to the reduction of wave energy (test case R). The model also reproduces the asymmetry in the sediment accumulation pattern, which is due to the obliquely incident wave. As for the longshore transport, a reduction is registered, dropping to 48% of the known value for the study zone. The circulation pattern around the structure is asymmetric and composed of two cells which are caused by the divergence of the currents generated in the SBW towards the coast.

Analysis of the crest height variation shows that, as the submergence level increases, the seabed elevation in the lee of the structure decreases. Increasing the distance to the coastline reduces both the influence of the SBW on its surroundings and the capacity to retain sediments in its lee. Regarding the SBW length, the model results show that its increase results in an increase of the sediment deposition in the lee of the SBW, tending to the formation of a T-shaped groyne.

The test with a less erosive wave, like the most frequent wave, has been done (test case F). The SBW induced effects on the shoreline were attenuated in comparison to the mean wave action results, dropping to 5% of the reference case (test case R). One concludes from these results that the SBW would more efficiently pro-

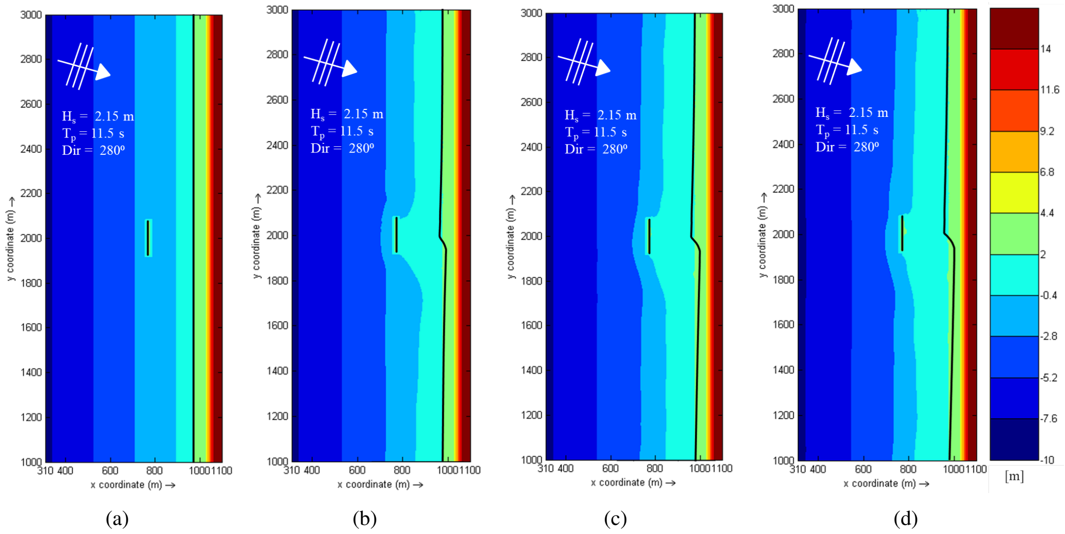


Figure 15: Bottom morphology in the vicinity of an emerged detached breakwater subject to a stationary wave (most frequent wave): (a) initial, (b) after 10 days, (c) after 20 days and (d) after 30 days. The colour scale [m CD] refers to delft3D model results and black line (2 m above CD) to LITLINE model results.

tect highly energetic coasts, like the portuguese coast.

Lastly, a comparison between the Delft3D and LITLINE models has been done for a comparable test case. The comparison of the two models made clear that the simplifications assumed by LITLINE do not allow for the model to correctly reproduce the structure's effect on the coastline's local evolution. The Delft3D model captures the circulation patterns that occur in the structure's vicinity, and between itself and the coastline, which influences the coastline's evolution. Because of this, Delft3D is better fit to simulate the alterations induced in the coastline by the presence of this kind of structure.

In the future, calibrating the Delft3D model with field data and performing tests with physical models for the same test case conditions of the Delft3D model is recommended, in order to further validate the numerical model.

References

Antunes, C. and Taborda, R. (2009). Sea level at Cascais tide gauge: data, analysis and results. *Journal of Coastal Research*, pp. 218–222.

Black, K. and Mead, S. (2001). Design of the Gold Coast reef for surfing, beach amenity and coastal protection: surfing aspects. *Journal of Coastal Research*, 29:115–130.

Black, K. P. and Andrews, C. J. (2001). Sandy shoreline response to offshore obstacles part 1: Salient and tombolo geometry and shape. *Journal of Coastal Research*, pp. 82–93.

Deltares. (2011)a. *Delft3D-FLOW, Simulation of multi-dimensional hydrodynamic flows and transport phenomena, including sediments, User Manual*. Delft.

Deltares. (2011)b. *Delft3D-WAVE, Simulation of short-crested waves with SWAN, User Manual*. Delft.

DHI. (2016). *LITLINE – Coastline Evolution, User Guide*. Danish Hydraulic Institute, Copenhaga, Dinamarca.

Giardino, A., Werf, J. V. D., and Ormondt, M. V. (2010). *Simulating coastal morphodynamics with Delft3D: case study Egmond aan Zee*. PhD thesis, Deltares Delft Hydraulics.

Oliveira, F. S. B. F. (2016)a. Modelling morphological evolution in the surrounding area of a groyne: preliminary results. 4^{as} *Jornadas de Engenharia Hidrográfica, IH*, pp. 257–260.

Oliveira, F. S. B. F. and Brito, F. A. (2015). Morphological coastline evolution south of the Mondego river inlet from 1975 to 2011, Proceedings of VIII. *Congresso sobre Planeamento e Gestão das Zonas Costeiras dos Países de Expressão Portuguesa, Universidade de Aveiro, Aveiro*. 15 p. (in Portuguese)

Oliveira, F. S. B. F., Ruas, J., and Trigo-Teixeira, A. (2018). Morphodynamics in the vicinity of a groyne with 2D and 1D numerical models. *5as Jornadas de Engenharia Hidrográfica*.

Oliveira, J. N. C. (2016)b. *Modelling the impact of the extension of the north jetty of the Mondego river inlet on the adjacent southern beaches*. Master's thesis, Instituto Superior Técnico, Universidade de Lisboa. (in Portuguese)

Ranasinghe, R. and Turner, I. L. (2006). Shoreline response to submerged structures: A review. *Coastal Engineering*, 53(1):65–79.

Santos, F. D., Lopes, A. M., Moniz, G., Ramos, L., and Taborda, R. (2017). *Coastal zone management: the challenge of change*. (in Portuguese)

Tomasicchio, U. (1996). Submerged breakwaters for the defence of the shoreline at Ostia field experiences, comparison. *Coastal Engineering*, pp. 2404–2417.

Turner, I. L., Leyden, V. M., Cox, R. J., Jackson, L. A., and McGrath, J. E. (2001). Physical model study of the gold coast artificial reef. *Journal of Coastal research*, pp. 131–146.

Vicente, C. and Pereira, M. (1986). Evolution analysis of the Figueira da Foz beach. *Laboratório Nacional de Engenharia Civil, DHA/NEC*. 51 p. (in Portuguese)