PHYSICAL MODELLING OF SAND-FILLED GEOSYSTEMS FOR COASTAL PROTECTION

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Abstract: Unidirectional irregular waves of varying significant wave-height and peak period but with a constant spectral shape (JONSWAP spectrum, γ=3.3) were generated over a sandy 3:20 sloped plane beach to investigate scour fronting a dune erosion control system constructed from geotextiles, slope inclined at 45º. Both passive (i.e., three dune erosion control systems with two configurations) and active (i.e., one nearshore submerged structure with four configurations) structures are investigated. A two-dimensional physical movable-bed model simulating the prototype dune-beach systems of Estela, located along the NW Portuguese coast, is employed in this study. The paper presents a brief characterization of the prototype conditions and discusses requirements and limitations on the choice of model scale for the waves, the sediments, and the geotextile materials.

Keywords: geotextiles, erosion, scour, beach lowering, movable-bed models.

1 INTRODUCTION

The application of geosystems in coastal engineering still has a very incidental character, and it is usually not treated as a serious alternative to the conventional solutions. The explanation for this lays on uncertainty, partly related to the lack of suitable design methods (see, e.g., Recio, 2007), and partly related to material durability and life-time performance (see, e.g., Pilaczyk, 2000).

Geotextiles as containment systems in coastal engineering have been used successfully as temporary structures (in emergency works or to learn the impacts on coastal processes and how they will affect the system and neighbouring systems), in shallow water and in low wave energy coasts with a low tidal range. They have as well been used successfully associated with regular artificial sand nourishment. However, their utilization as a permanent structure in high wave energy coasts carries several implications and is so far unproven.

In the present work, which is a summary of das Neves (2011), physical modelling is used to study the stability of sand-filled geosystems under wave loading with emphasis on the issues of scour development and more widespread beach lowering. Early work in the area of the application of geosystems in coastal engineering include: van Steeg and Vastenburg (2010) on large scale model tests on the stability of geotextile tubes; Oumeraci and Recio (2009) on geotextile sand containers for shore protection; van Steeg and Breteler (2008) on large scale physical model tests on the stability of geocontainers; Recio (2007) on the effect of deformations on the hydraulic stability of geotextile sand containers for coastal structures; Recio and Oumeraci (2007b) on the permeability of geotextile sand containers; Recio and Oumeraci (2007c) on the processes affecting the hydraulic stability of geotextile sand-filled containers; Oumeraci et. al. (2002) on the hydraulic stability of geotextile sand containers under wave loading; and Bezuijen et al. (2004), Bezuijen et al. (2002a, 2002b), and Bezuijen et al. (2000) on field and model tests on the placing accuracy and stability of geocontainers. The book by Pilarczyk (2000) has covered developments which took place until late nineties, and is still a valuable reference for a comprehensive understanding of geosystems in coastal engineering.

The research programme described in this paper focus on scour development and beach lowering, to investigate the efficiency of various geosystems in maintaining a beach and in protecting the shoreline.

The analysis is based on a series of laboratory measurements of wave-induced morphodynamic changes. A beach located at the northwestern Portuguese coast was used as prototype.

Five models, matching to three dune erosion control systems with two configurations, one nearshore detached breakwater with four configurations and one non-protected dune-beach system (hereafter designated as Model A) as reference were taken for the investigation. The models were submitted to a total of ten different sea-states (*i.e.*, combinations of four significant wave-heights and four peak periods), which corresponded to balance conditions of erosion, accretion, persistent erosion, and erosion followed by infilling and again erosion.

2 DESCRIPTION OF THE PROTOTYPE DUNE-BEACH SYSTEM

The *Estela Golf* course is located in *Estela*, a municipality of *Póvoa do Varzim*, approximately 9km north of its city harbour and just south of a coastal protected area (Figure 1). It is situated along the north-western coast of Portugal in a 3km-long dune system. Dredging activities at the River *Cávado* and morphological changes in the river basin caused the decrease in the volume of sediments transported by the littoral drift. The completion of other groynes and seawalls, namely in the sand spit of *Ofir* and in the coast of *Cedo Bem* and *Apúlia*, further aggravate that reduction by retaining some more sediments.

Figure 1. Aerial view of the beach-dune system of Estela (photo by Francisco Piqueiro).

The first documented intervention, done during the period of 1 to 12 April 1999, consisted of located reinforcement of the dune toe through mechanical ripping with sand from the frontal beach and consolidation of this sand deposit with wood piles and small 5kg sand bags (Veloso-Gomes et al., 2006). Since then periodic interventions consisting of the piling up of beach sediment to the dune and replacement of tear, lost or displaced bags occur. Table 1 summarizes the total cost of interventions per year from 1999 to 2009. The average cost per year is around 25,000.00€, 15% of which corresponds to material costs. The higher costs on Table 1 are associated with years of more frequent storms regardless its intensity. This was the case in 2000/2001 and again in 2009.

Figure 2 show some recent images of the dune taken on the winter and spring 2009/2010.

The prototype conditions to be replicated in the physical experiments are the average cross-shore beach profile (i.e., beach slope, dune slope, and dune crest height and base position), wave conditions, and sediment properties (i.e., grain size-distribution and particle characteristic diameters).

Table 1. Total cost of interventions from 1999 to 2009 (source: *Estela Golf*, S.A.).

Year	Cost (in Euros)	No. of bags (approx)
1999	27,433.88	-
2000	52,373.78	-
2001	44,570.12	2983
2002	16,736.00	1620
2003	20,085.40	1960
2004	8,681.00	660
2005	3,945.00	-
2006	9,853.50	1150
2007	9,837.00	150
2008	25,050.52	2637
2009	43,309.60	3212
Total	261,875.80	14372

Figure 2. Views of the dune-beach system of *Estela*, March 2010.

3 EXPERIMENTAL SETUP

The experiments have been conducted in a partition of the wave basin of the Hydraulics Laboratory of the Hydraulics (LH), Water Resources and Environment Division (SHRHA) of the Department of Civil Engineering (DEC) of the Faculty of Engineering of the University of Porto (FEUP), which is 28m long, 12m wide, and 1.2m high but was partitioned to a wave channel of 2.25m wide, comprising 3 wave-paddles out of the 16 comprising the HR Wallingford multi-element wave generation system available at LH SHRHA-DEC-FEUP. At one end irregular waves of varying significant wave-height and period but with a constant spectral shape (JONSWAP spectrum, γ=3.3) were generated in a working water depth of 0.58m, which corresponds to the mean water level in prototype.

A plane beach (gradient β=0.15) starts 9.7m from the wave paddles followed by a dune (or erosion control system). Surface elevations were recorded seaward the beach slope from an array of four wave probes with known spacing. Pore-pressure sensors of 9mm diameter were installed to study wave-induced pore pressure variations.

The beach-profile was surveyed at the end of each wave-run segment using a 2D bed profiler that drives along a support beam. The origin of the horizontal co-ordinate, x, and the origin of the vertical co-ordinate, z, is taken as the intersection of the still water line with the beach face, positive onshore. A 10 cm square grid was installed on the glass wall of the basin allowing the visual inspection of profile changing during experiments and providing a reference in viewing the visual recording of the tests.

Time-series data and profiles were collected from over 150 movable-bed tests, with different models and wave conditions.

3.1 Wave Conditions

The incident waves were chosen from the statistical analysis by Coelho (2005) of the data recorded by the oceanographic buoy at Leixões from 1981 to 2003. From this study is possible to find that the significantly more frequent wave heights range from 0.5 to 2.5m, with ~72% of cases. The maximum wave height being recorded was 9m. Wave-heights higher than 2.5m correspond to ~27%, from which no more than 11% above 5.5m. Only 1% of the records correspond to waves lower than 0.5m. The more frequent values of wave period vary between 7 and 11s, with less than 4s and higher than 17s as minimum and maximum observed respectively.

The controlling factors with respect to the limiting values of the period and height of the model waves were determined in correspondence with the statistical analysis provided in Coelho (2005) along with the threshold of maximum wave-height that can be achieved at a particular frequency which is limited by either the performance of the wave generation system (maximum stroke, velocity and force achievable) or the wave breaking.

The experiments were conducted only for irregular waves, because as has been demonstrated many times by several authors the use of regular waves with height and period equal to those of significant wave can give inconsistent or erroneous results in the analysis of wave transformation and action of waves (see, e.g., Goda, 2000).

3.2 Considerations on the Choice of Model Scale

While selecting the scaling criteria and scale ratios of the movable-bed model, the following general principles were assumed:

- Geometrically undistorted model;
- Nearshore hydrodynamics parameters to be modeled according to Froude similarity;
- Movable-bed model to be composed of sand material;
- Suspended load transport to be the dominant mode-of-sand-transport;
- Selected model length scale should be made as large as possible so that the character of the wave breaking process is properly simulated, *i.e.*, so that viscous and surface tension effects are negligible.

The first approximations to the beach slope and sand material in the model have been derived from prototype. As far as the beach slope is concerned, it was kept as a plane slope for most of the experiments, to facilitate the direct comparison of the measurements. With respect to the sand material, sediment transport scaling rules, as described in *e.g.* Hughes (1993), Oumeraci (1993), and Dalrymple (1985), based on samples collected from the prototype in two beaches along the NW Portuguese coast at different positions along- and across-shore were calculated. Sieving curves of both the sands, prototype (given as the average curves at similar positions across-shore) and model (referenced as SP55), are given in Figure 3.

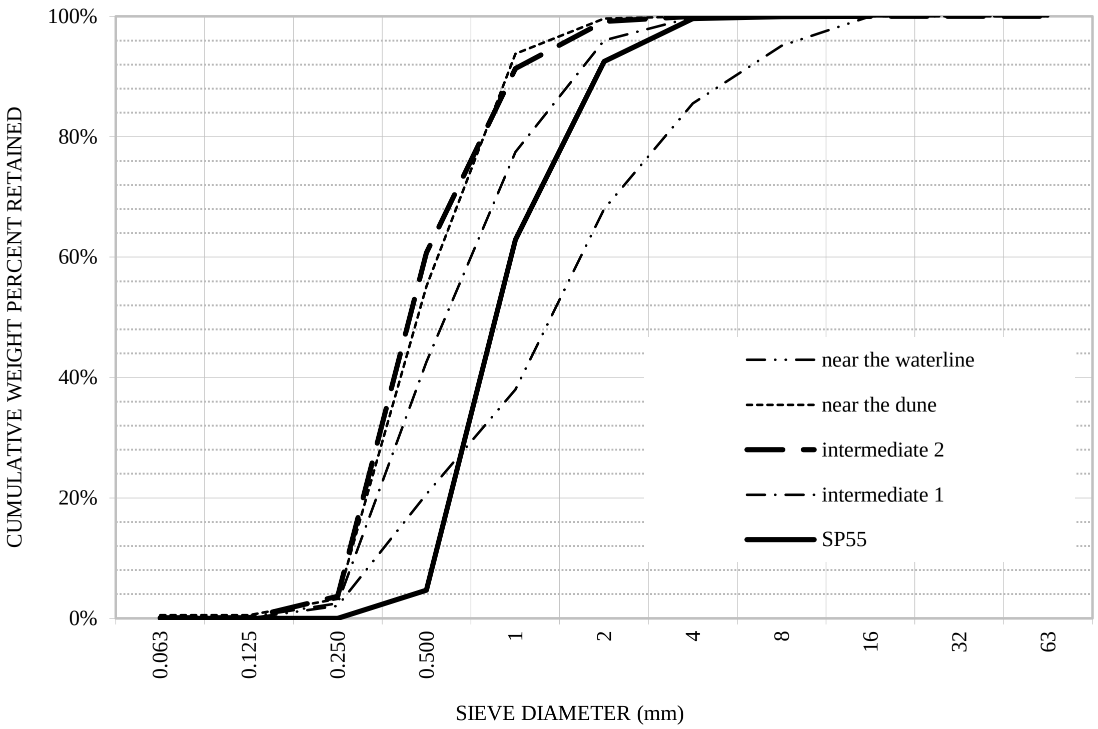

Figure 3. Prototype and model sediment grain size distributions.

According to Hughes (1993), in the nearshore region, turbulent water motions play a greater role in mobilizing and transporting sediment; and in this region there is increasing evidence that the dimensionless fall speed parameter, should be similar in both prototype and model.

Van Rijn (2006), Jiménez and Madsen (2003) and further references cited therein include several of the most important formulas to compute the fall speed of natural sediments, for example, Zanke (1977), Hallermeier (1981), Dietrich (1982), van Rijn (1984), Julien (1995), Soulsby (1997), Cheng (1997), Sistermans (2000), Ahrens (2000, 2003), and Jiménez and Madsen (2003), for quartz particles, and for calcareous particles the ones from van der Meulen (1988), and Smith and Cheung (2003). In the current investigation, the sediment fall speed of both the sands, prototype and model, were calculated using Hallermeier's relationships (see, e.g., Hughes, 1993).

The chosen length scale model, N_L, was 12. Refer to das Neves (2011) for further detail on the choice of model scale.

3.3 Sand-filled Geosystems

Three types of geosystems were used in the model tests; sand-filled containers, and sand wrapped around geotextile sheets made from commercially available non-woven geotextile filters, and geotextile tubes of different sizes made from commercially available woven geotextile filters.

Although the geosystems used in the model tests are made from commercially available geotextile materials, it is not possible to use the geotextile that is used in the prototype. The following scaling aspects were considered: stiffness and tensile strength of the geotextile during wave experiments; stiffness and tensile strength of the geotextile during filling; and sand tightness.

Table 2 gives a summary of some properties of the prototype and model geotextiles. As can be easily demonstrated complete similarity of the geotextile properties is impossible, as for example the thickness scale would be equal to the length scale (N_L), whereas the tensile strength scaling would have to be the square of the length scale (N_L^2), and the water permeability scale would have to be equal to the square root of that scale ($N_L^{-1/2}$). A comprise is thus necessary while scaling down material properties.

Table 2. Summary of material properties in prototype and model.

Property	Unit	Woven		Non-woven	
		Prototype	Model		Prototype
Raw material	-	PP	PE	PES	PP
Mass per unit area	g/m^2	1000	300	1000	300
Thickness	mm	-	-	5.3	1.6
Tensile strength	kN/m				
MD: machine direction		198	40	30	13
CMD: cross machine direction		189	20	50	22
Elongation at nominal strength	%				
MD: machine direction		15	20	50	50
CMD: cross machine direction		11	20	40	30
Characteristic opening size	μm	416	230	70	70
Water permeability	l/(s m^2)	20	65	10	40

Refer to Morais (2010) for further detail on the characterization of the properties of the prototype and model geotextiles taken for this investigation and on possible scaling effects due to non-satisfied scaling criteria.

Figure 4 presents a sketch of Models B to D, variants 1 and 2, and Model E, variants 1 to 4 being investigated. A fifth model of a non protected dune-beach system, Model A, has been used as a reference case.

The 3 different erosion control geosystems employed in these experiments were: several individual geotextile sand-filled containers, designated as Model B (top panel in Figure 4); a wrapped-around system, designated as Model C (middle panel in Figure 4); and geotextile tubes designated as Model D (bottom panel in Figure 4). Each one of the models had two variant configurations, 1 and 2 that differ in the position of the structure toe, placed at level +0.00m (SWL) that is (x,z)~(0.16,-0.16), and +2.00m (SWL) that is (x,z)~(0.31,0), respectively. All models have the crest height at approximately 0.42m (+7.00m in prototype) and were built with a 1:1 slope.

The nearshore submerged breakwater (Model E) configurations were deduced from the definition parameters, position to the shoreline, and submergence. The latter was kept constant at 0.165m. With respect to the former, the locations of the submerged nearshore breakwater were off-shore zone, surf zone and an in-between locations having Model A as reference. The rationale for defining the location of the nearshore submerged structures was defined with basis on the standard equilibrium beach-profile shape proposed by Dean in 1977 (see, e.g., USACE, 2008). Refer to das Neves (2011) for further detail.

This model was constructed from geotextile tubes, either as stacked tubes, E1 (six small stacked tubes, 3-2-1 stack) and E2 (three small tubes placed behind each other and a fourth medium tube on top, 3-1 stack), or single tubes, E3 (one medium tube) and E4 (one small tube), see Figure 4.

The dimensions of the geotextile tubes used to build Model E correspond to the diameters, in prototype, of ϕ1.60m, and ϕ3.25m. The key theoretical parameters that relate the diameter of the tube with its dimensions when filled are the ratio maximum height to diameter (H/D~0.6), and the ratio base-width to diameter (b/D~0.9). In the model such relationships, between diameter and maximum height, and between diameter and base-width, differ slightly from those in prototype. The tubes were filled with the same clean silicate-sand.

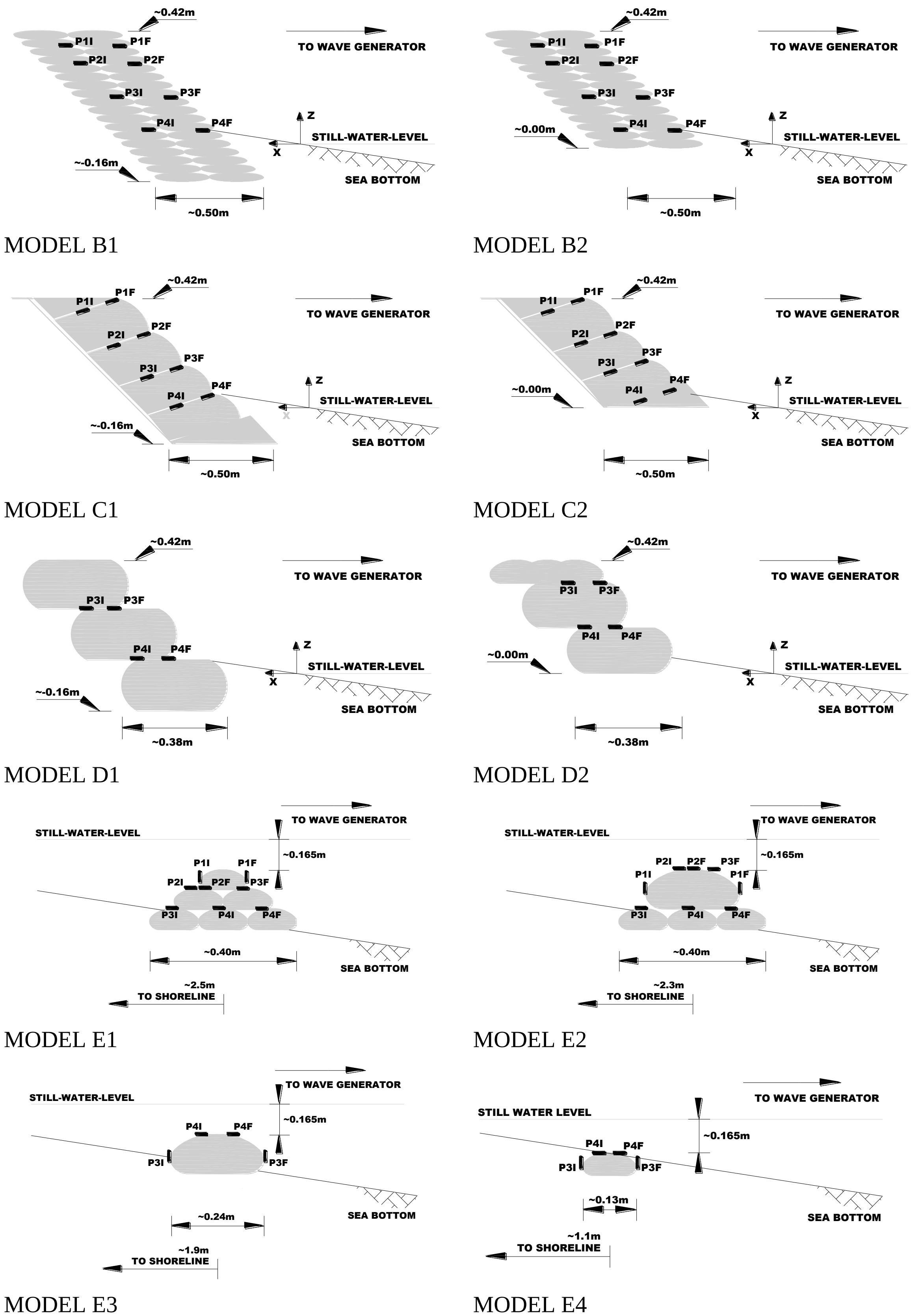

Figure 4. Sketch of Models B to D, variants 1 and 2, and Model E, variants 1 to 4, from top to bottom respectively (not to scale, P marks the location of the pore-pressure sensors).

4 RESULTS AND DISCUSSION

The carried out experimental work aimed at *(i)* the stability of geotextile encapsulated sand-systems against scour and more widespread beach lowering; *(ii)* the cross-shore component of sediment transport to study the response of a dune-beach system under conditions of erosion, accretion, persistent erosion and conditions alternating between periods of erosion and accretion; and *(iii)* the comparison of four different coastal protection schemes against each other, and against a reference case. For this purpose different models of active and passive coastal defence structures were set-up to run on similar hydrodynamic and morphodynamic conditions. The intercomparison carried out on the hydrodynamic and morphodynamic outputs produced by each scheme focused on the scour and deposition patterns over the test period evaluated on the parameters deepwater wave characteristics, reflection coefficient, and wave-induced pore-pressures. The next step was to increase understanding of the response of the beach under persistent erosional conditions and under periods of erosion followed by infilling and again erosion.

In the assessment of the overall performance of each coastal protection scheme five perspectives were considered: stability of geotextile encapsulated sand-systems under wave-loading; scour-depth development: scour holes development and scour-and-deposition patterns over the cross-shore length of the model; observations of erosion and backfilling during a test duration; dependency between scour-depth and non-dimensional variables as given in the literature; storm response: changes in cross-shore beach-profile when exposed to storm conditions lasting for a test duration of 30 minutes; beach levels drawdown at the structure and more widespread beach lowering; recovery between storms: response to the changing forcing conditions; build up during swell conditions, followed by beach levels drawdown during storm conditions; volumetric changes due to seasonal variability; and coastal evolution: beach-profile change under persistent erosional conditions.

Some selected results are briefly described next, more detailed information can be found in das Neves (2011).

A comparison between the initial plane beach and the end measured profiles for one selected sea-state is presented in Figure 5 for the passive coastal defence structures, models B to D, variants 1 and 2, and in Figure 6 for the active coastal defence structures, Model E, variants 2, 3, and 4. The measurements with Model E, variant 1, have not been included in the analysis because the test was interrupted when the structure became unstable after approximately 11mn wave action (Figure 7). Model A, the initial dune-beach system profile and a sketch location of the submerged nearshore detached breakwaters are given as reference.

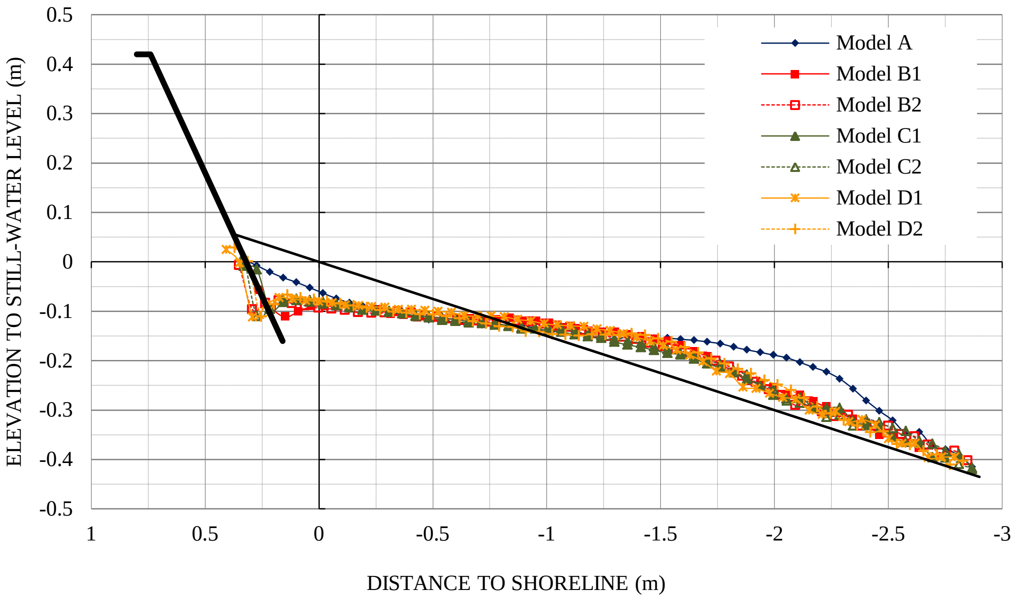

Figure 5. Comparison of initial and end beach profiles for sea-state 8 (H_s=2.0 m, T_p=10 s, in prototype).

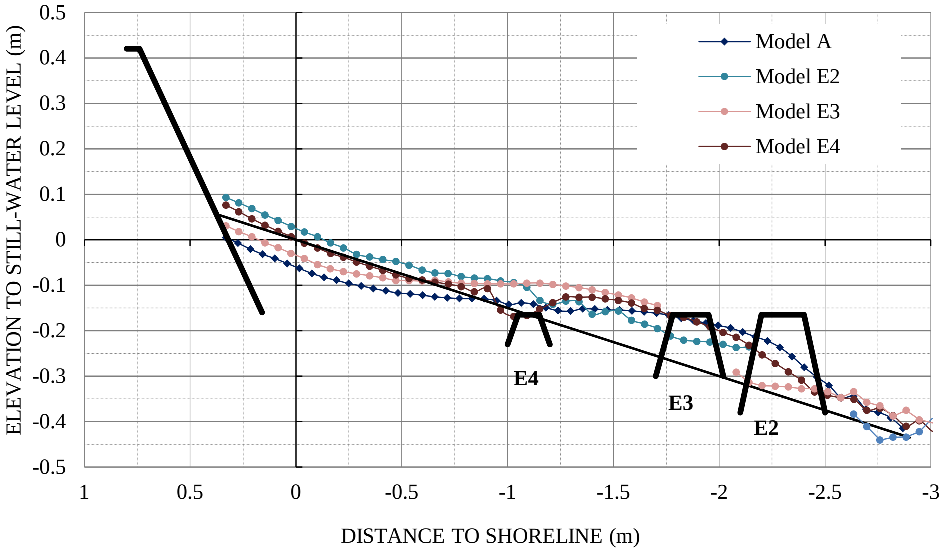

Figure 6. Comparison of initial and end beach profiles for sea-state 8 (H_s=2.0 m, T_p=10 s, in prototype).

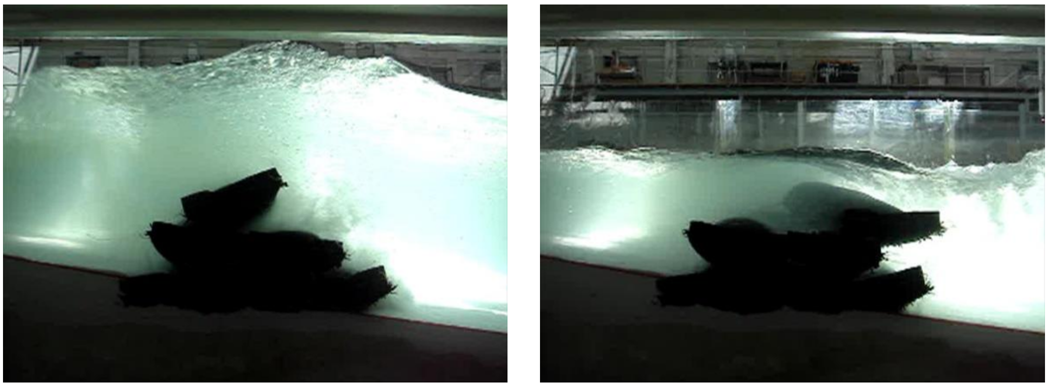
Figure 7. Model E1, sea-state 10 (H_s=0.125 m, T_p=2.89 s): model become unstable after *ca.* of 11 min wave action.

Figure 5 show that the beach-profile change is similar in the examined cases. The shoreline has retreat as far as the established structure and a nearshore-bar has developed. The erosion in the vicinity of the shoreline roughly equalled the accumulation in the bar area, indicating that the sand was transported from the beach and deposited near the main breaker line; some of it was carried even farther offshore (*e.g.*, in the cases where the beach-profile was exposed to persistent erosional conditions).

The bar accumulation in the case of Model A is greater as compared to the other cases in analysis, especially during the higher waves; while the shoreline recession is much smaller. Although these may presumably be expected morphologic change given that the sands eroded from the dune would be transported to the beach, it is remarkably striking to realize that the net volume changes in Model A are substantively higher than in the other models which corroborates Dean's approximate principle, *i.e.* eroded volume is less than or equal to volume retained by the structure had it not been in place (see, *e.g.*, USACE, 2008). The distance of the bar to shoreline is similar between models but that distance is generally longer in variants 2.

It is clear from the preceding results and figures that there was a lowering of the beach levels around the various passive coastal protection schemes. Under persistent erosional conditions (even under constant wave-height) the beach level fall as low as the baseline across the entire profile as a result of a cross-shore profile migration; within which the sediments initially deposited at the lower beach face move further seaward, thereby extending the bar, with time a double bar along the beach-profile starts to develop, as sediments are moved offshore and a moderately deep trough starts to build up. The analysis of the computed volumetric changes, reveal that the incidence of higher values of cumulative volume lost is in straight connection to the volume of sand deposited in the nearshore-bar (das Neves, 2011).

Figure 6 show that in Model E2 and E4 the main morphologic changes occur in the lower beach, whereas at the upper beach the end profile varies slightly from the initial one. Some moderate shoreline accretion was though observed in Model E2 wave run-segments; while in Model E4 the shoreline has prograde only under sea-state 10 (refer to das Neves, 2011).

The results on scour development indicate that under the most energetic sea-states (7, 8 and 9) the normalized scour depth at models B to D typically increased as the steepness of the incoming wave increased, but decreased with an increase in the water depth at the structure (*i.e.*, Model E). It is also seen that for models B to D the normalized scour depth generally increased with increase of the surf similarity parameter. In regard to water depth at the structure to deepwater wavelength ratio, the scour depth generally increased with decrease in that ratio, whereas it decreased with distance to deepwater wavelength. Further it decreased with decrease in the coefficient of wave reflection, but increased with an increase in incident wave-height (*i.e.*, is lower for sea-state 10 as compared to sea-states 7, 8, and 9) and decreased with an increase in the water depth at the structure.

Overall, the results from the laboratory measurements point out that the maximum scour depth under erosional waves decreased with an increase in the water depth at the structure (*i.e.*, is lower in Model E) but increased with waves breaking near the toe of the structure (Model E4). They also indicate that the scour depth is influenced by the mechanisms of wave reflection off the structure and wave downrush flow on the exposed slope. Furthermore, the experimental results showed that the scour depth around geosystems is of the order of magnitude of the unbroken wave-height.

5 CONCLUSIONS

The coastal mobile bed sediment transport and morphology model is perhaps the most difficult of all physical hydraulic models (Kamphuis, 2009); yet despite the shortcomings it is, in many cases, the most important available instrument to bring about improvements with respect to sediment transport, and erosion.

This paper has described some of the rationale behind the implementation of a two-dimensional physical movable-bed model simulating the prototype dune-beach system of Estela, located along the NW Portuguese coast, which has been employed in an experimental effort to study scour development and more widespread beach lowering around sand-filled geosystems.

As it has become clear complete similarity between prototype and model is impossible and thus scale effects with respect to hydrodynamics, morphodynamics, and material properties are introduced in the model. The understanding of the effects those dissimilarities have in the experimental results is crucial to their extrapolation to a natural situation. For example, dissimilarity on the scaling of the movable-bed material introduces scale effects that will affect the initiation of sediment motion, the sediment transport mode, and the sediment transport rate and thus their impact must be considered while interpreting results. It has become clear as well that such effects are far less understood and studied for geotextile materials than for waves, and even sediment transport.

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