Analysis of S. João da Caparica beach vulnerability to a maritime storm event

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Abstract: The morphological response of the S. João da Caparica beach, Almada, to the maritime storm Hercules that occurred in January/2014, was studied through mathematical modelling, for three of twelve topo-bathymetric configurations surveyed between 2008 and 2017: the two with the lowest and the one with the highest volume of sediment in the topographic part. This study aimed to quantify indicators of beach vulnerability, such as sand volume above three reference vertical levels, average and maximum retreat of two reference isobaths and maximum topo-bathymetric lowering, in order to provide guidance for future nourishment interventions. Hydrodynamic models at regional and intermediate scales were used to determine the forcing of the morphodynamic local model applied, XBeach. Besides the beach vulnerability indicators, the results revealed that the morphological configuration of the submerged zone plays an important role in the beach response when submitted to a storm with the characteristics of Hercules.

Key words: Costa da Caparica beach, extreme maritime event, sediment dynamics.

1. INTRODUCTION

This study is part of a set of morphodynamic coastal studies based on numerical modelling developed to provide guidance for optimized decision-making on future coastal protection interventions in Costa da Caparica, Portugal.
The Costa da Caparica coastal stretch suffered relevant morphological variations since 1929, with the retreat of the spit that initially extended to the Bugio lighthouse and the retreat of the coastline in the maritime front of Costa da Caparica. The major structural interventions of coastal defense were built between 1959 and 1971. Since then until the 2000/2001 maritime winter the stretch was fairly stable. However, after this date beach erosion and structural overtopping imposed emergency interventions, such as the mechanical ripping of sand from the beach face to reinforce the dune and the repair of the damaged defense structures, in the winters of 2002/2003, 2003/2004 and 2006/2007. Between 2007 and 2014 3.5 million m^3 of sand were deposited in the emerged part of the beach.
The objective of this specific study was to quantify the morphological response of the Costa da Caparica beach to an extreme maritime storm for different initial morphologic states of the beach. In particular, to evaluate the beach vulnerability indicators, namely the coastline retreat, the surface lowering and the volume of sand loss in between vertical levels.
The total study zone (Figure 1) includes the coastal stretch limited at NW by the groyne EV1 and at SE by the SE extreme of the alongshore defense structure of Costa da Caparica. However, this paper focuses only in S. João da Caparica, the 1.4 km long beach, located at the NE extreme of the stretch, between groynes EV1 and EC7, which are 360 and 140 m long, respectively. The coastline of S. João da Caparica has an average alignment of 140ºN in the NW and central sectors and of 150ºN in the SE sector. The NW and central sectors have a dune system that reaches an elevation of about 11 m above the zero of the nautical vertical reference level, ZH. The SE sector has a 460 m long alongshore defense structure, which limits the expansion of the natural beach profile.
Silveira *et al*. (2013) quantified the impact of a storm event in S. João da Caparica on 19/Jan/2013 through high resolution topographic surveys. These surveys, performed on the 2/Dez/2012 and 21/Jan/2013, revealed that during this period the erosion between the Mean Sea Level (MSL) and High Equinoctial Spring Tidal Level was 50×10^3 m^3, and that the total extent of the coastline retreated, with average magnitude 20 m and maximum value 41 m in the SW sector.

2. METODOLOGY AND DATA

2.1 Numerical modelling

The numerical modelling of the beach morphodynamics was performed with the 2DH Surfbeat mode of the XBeach model (Roelvink *et al*., 2009), which accounts for infragravity waves and dune avalanche, among other mechanisms determinant during a storm event. The evolution of the topo-bathymetry in the active zone of the beach, which includes the surf zone, the beach face, the berm and the dune, was simulated for three initial morphological states of the beach. A staggered grid with a uniform grid size of 5 m in both directions was applied, implemented in a coordinate system where the x-coordinate is oriented approximately perpendicular to the coastline.

The XBeach model was forced at the offshore boundary with hydrodynamic data (sea level and waves) obtained through the application of hydrodynamic numerical models, previously calibrated and validated, at regional and intermediate scale. The tide and the wave generation and propagation were simulated at regional scale in the NE Atlantic Ocean with respectively the SCHISM model (Fortunato *et al*., 2019) and the WaveWatchIII model forced with predictions of the European Center for Medium-Range Weather Forecasts (Fortunato *et al*., 2017a). The results of these two models were then used do simulate the hydrodynamics at an intermediate scale with the SCHISM-WWM model, previously calibrated and validated (Fortunato *et al*., 2017b), in a domain that includes the full Tejo estuary and an area of the coastal zone adjacent to the mouth. The tide, the atmospheric forcing (wind and atmospheric pressure), the waves and the fluvial discharge were considered.

Fig. 1. Aerial photograph of S. João da Caparica beach between groynes EV1 and EC7. Location of profiles PCC3, PCC5 and PCC7, used in the calibration of XBeach. Points P2, P3 and P4 of hydrodynamic data (© Google Earth).

2.2 Topo-bathymetry

Three initial morphological states of the beach, two unfavorable (post-storm) and one favorable (post-nourishment) were defined based on the analysis of twelve topo-bathymetric surveys of the total study zone (not exclusively the S. João da Caparica beach) performed between Jul-Aug/2008 and Dez/2017. Considering the survey of Jul-Aug/2008 as a reference, the volumes of sand above the levels -9, -1 and +2 m ZH were calculated for each survey.

The DTM with the lowest and second lowest volume of sand above the levels -1 and +2 m ZH, which correspond to the surveys of Jul-Aug/2008 and Jul/2014 respectively, were considered the most unfavorable and the second most unfavorable morphological states and designated as Case I and Case II. In contrast, the DTM with the largest volume of sand above the levels -1 and +2 m ZH, which corresponds to the survey of Nov/2008, was considered the favorable morphological state and designated as Case III. The grain size diameters D_{50} and D_{90} were considered 0.3 mm based on field data.

2.3 Maritime storm

The Hercules storm, which occurred in the first fortnight of January/2014, was considered. The duration of the storm was taken as the time period between the dates of the first and the last value of a series of $Hs > 4.5$ m with minimum length 24 h, provided that during the following 48 h no values of $Hs > 4.5$ m occur. For the Hercules storm, the duration was 93 h and 10 min (3,88 days), between 2014-01-04 04:00 and 2014-01-08 01:10 (yyyy-mm-dd hh:mm). The storm registered two peaks of Hs offshore Costa da Caparica, the first equal to 5.91 m and the second equal 7.05 m (Figure 2).

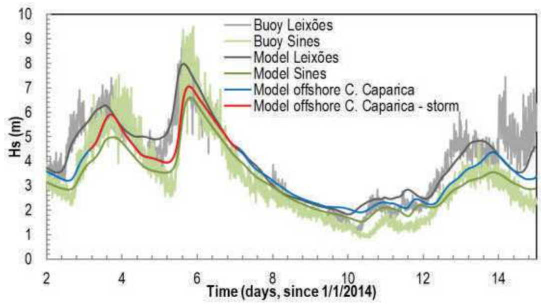

Fig. 2. Significant wave height, Hs, in the first fortnight of Jan/2014: Leixões and Sines buoys data and WW3 model results, and offshore Costa da Caparica SCHISM-WWM model results.

2.4 Models validation

The period of validation of the morphodynamic model was two months, 1/Set - 31/Oct/2014, which was the shortest period of time between topo-bathymetric surveys of the total study zone. The hydrodynamic forcing was provided by the intermediate scale model (SCHISM-WWM), which was validated against buoy data from the Lisbon Port Authority (Figure 3). The XBeach model (2DH version with two cells alongshore) was applied for three equidistant profiles, PCC3, PCC5 and PCC7 (Figure 1). Its performance was evaluated through i) impact indicators, such as the volume of erosion per meter of alongshore beach length and the horizontal beach retreat at levels -1, 0 and +2 m ZH; and ii) an error indicator, the Brier Skill Score (BSS) proposed by Van Rijn *et al*. (2003). The evolution of PCC5 in the central sector can be seen in Figure 4. According to the value of the topo-bathymetric survey error, δ, considered δ=0.15/0.3 m, the classification of the model performance varies between reasonable and good: for profile PCC3 is reasonable, BSS=0.5/0.6, and for profiles PCC5 and PCC7 is good, BSS=0.7/0.8.

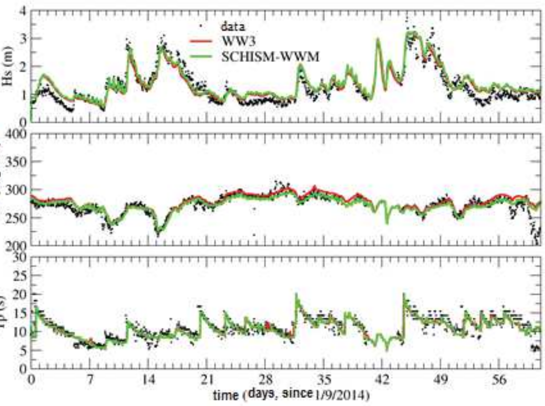

Fig. 3. Validation of the wave climate models: hindcast values against buoy data (Hs, above; Dir, middle; and Tp, below).

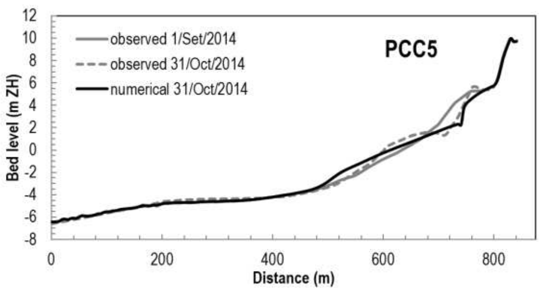

Fig. 4. Validation of the morphodynamic model for profile PCC5.

3. RESULTS AND DISCUSSION

3.1 Wave climate and sea level

The wave parameters and sea level series forced at the offshore boundary of the morphodynamic model were obtained from the hydrodynamic model at intermediate scale in points P2, P3 and P4 pointed out in Figure 1. They highlight that the NW sector of the S. João da Caparica beach is slightly more protected from higher waves than the central and SW sectors and also that the incident waves in the NE sector are more oblique relative to the cross-shore direction than in the central and SW sectors (Figure 5). The tidal modulation of the wave direction is significant (Figure 5), and justifies the use of a coupled tide-wave model of the estuary to provide the boundary conditions for Xbeach.

3.2 Morphodynamics and vulnerability

The 2DH-morphodynamic model simulations of the impact of Hercules storm in S. João da Caparica beach revealed the following:

- The storm caused morphological variations in all the alongshore beach extension. It smoothed out the bed irregularities by filling local depressions (e.g. of Case I in Figure 6).
- The largest lowerings of the beach occurred in front of the alongshore defence located at the SW sector and at the NW extreme of the beach. Large values of lowering were also observed at the head's toe of EC7 and at the toe of the offshore half of EC1 (e.g. of Case I in Figure 6).
- Despite the absence of a correlation between favorability of the morphological state and the erosion or the residual volumes, Case III remains as the one with larger sand volume above levels -1 and +2 m ZH after the storm (e.g. of cross-shore profile located at the central section in Figure 7).
- The erosion and residual volumes above the -1, 0 and +2 m ZH levels were larger in Case III than in Case I (Table I). Since the lower part of the beach is similar in both cases (Figure 7), the cause of the different morphological beach response was the larger volume of sand available in the upper part of the beach in Case III that was provided by the 1 million m^3 nourishment of Aug/2008.
- The erosion and residual volumes above -1 m ZH in Case II are the highest of all cases. However, the erosion is predominantly located between level -1 and 0 m ZH. Above +2 m ZH the residual volume is the lowest of all cases (Table I). When comparing with Case I it can be concluded that this is due to two factors: the smoothest slope of the active zone, which slows down the energy dissipation (spilling breaker type), and the highest sand volumes above -1 and +2 m ZH levels of Case II (Figure 7).
- The erosion of the upper beach caused a generalised retreat of the isobath +2 m ZH, with maximum value 21 m in Case III, and a generalised advance of the isobath 0 m ZH, with maximum value of 27 m in Case II.

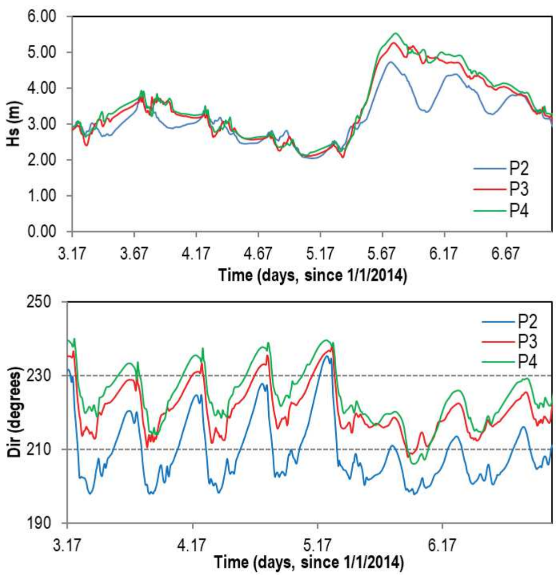

Fig. 5. Wave climate parameters series at the entrance of the morphodynamic model: significant wave height, Hs (above), and average direction, Dir (below).

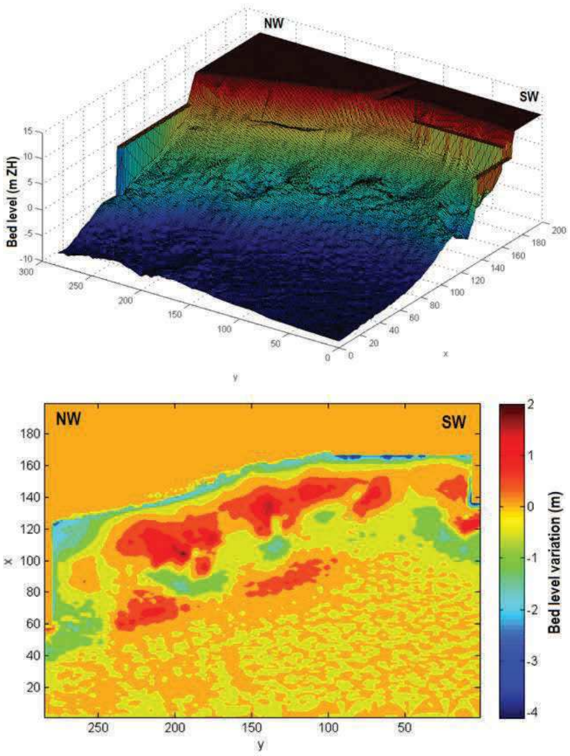

Fig. 6. Morphodynamic model results for Case I: pre-storm topo-bathymetry (above) and morphologic variation (below).

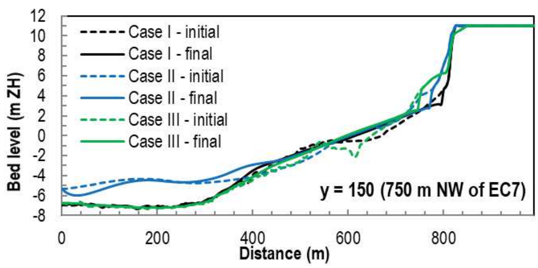

Fig. 7. Morphodynamic model results for Cases I, II and III: morphologic variation at a profile located in the central beach sector (750 m NW of EC7).

Table. I. Erosion, sedimentation and residual area and volume above levels -1, 0 and +2 m ZH in Cases I, II and III.

Zone	Case	Area (m^2)	Sedimentation volume (m^3) *(a)*	Erosion volume (m^3) *(b)*	Residual volume (m^3) *(a-b)*
Above -1 m ZH	I	605 020	71 737	78 913	-7 176
	II	644 503	64 212	112 122	-47 910
	III	628 999	65 688	91 841	-26 153
Above ZH	I	504 795	35 159	66 055	-30 896
	II	555 759	40 195	76 930	-36 735
	III	547 729	28 767	80 491	-51 724
Above +2 m ZH	I	407 121	817	56 910	-56 093
	II	403 569	795	37 524	-36 729
	III	431 710	303	66 726	-66 423

4. CONCLUSION

The study aimed at simulating the response of the S. João da Caparica beach to the Hercules storm for three morphological states, defined based on the analysis of twelve topo-bathymetric surveys of the active zone. The performance of the morphodynamic model was evaluated as good.

A set of parameters that characterise the impact of the storm on the morphology was calculated for the three cases. Among those parameters, it was calculated the residual erosion volume above the +2 m ZH level: 56, 37 and 66 thousand m^3 of sand. These values agree with the measured 50 thousand m^3 caused by the storm that occurred on 19/Jan/2013. The results also revealed that the morphological features of the active zone, such as the slope of the submerged zone, which affects the rate of the energy dissipation, play an important role in the beach response.

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