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A Hybrid Monitoring-modelling Analysis on the Storm Induced Sediment Dynamics of a Structure-controlled Beach

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ABSTRACT

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The main objective of this study is to investigate the effect of sediment flushing on the morphology of artificially embayed beaches using field data and numerical modelling. The sandy stretch of Cova-Gala in the West Coast of Portugal, characterized by a high-energy wave climate, is critical regarding erosion-flooding risks. The site was monitored from August 2018 to February 2019, including the wave climate, the sea level and the beach topo-bathymetric elevation via sonar-single beam, GNSS-RTK and drone surveys. During this period several erosive events caused the retreat and lowering of the upper beach profile. The XBeach model was applied to simulate the morphological evolution during the monitored period using synoptic wave and sea level data as the hydrodynamic forcing. The results of the data-model analysis reveal that i) the alongshore extension of the sedimentological cells and the cross-shore structures length have a relevant influence on the lee-side erosion patterns, which affect the overall surrounding morphology, ii) the model overestimates the scouring of the seawall toe, particularly with the 1D mode; and iii) the beach backshore typology, dune and seawall, has a great influence on beach dynamic processes.

ADDITIONAL INDEX WORDS: *Beach morphodynamics, numerical modelling, coastal monitoring, XBeach, erosion.*

INTRODUCTION

As one of the most energetic and dynamic coastal regions in Europe, the Portuguese West Coast has a high index of exposure to coastal erosion and flooding. The rise of the mean sea level and the expected increase of frequency and intensity of maritime storms increase this risk. The defense schemes implemented in the 70s can benefit from a reevaluation considering the latest developed numerical models that simulate the hydrosedimentologic structure induced processes.

Process-based morphodynamic models, such as XBeach (Roelvink *et al.*, 2009), are able to simulate the complex surf zone-beach hydro-morphological processes for simplified cases, allowing the identification of driving mechanisms and the study of interactions between different structures for controlled test conditions (Oliveira, Oliveira, and Trigo-Teixeira, 2016). Yet, little is known how the processes involved in the sea-structure-sediment interactions affect the surrounding morphodynamics and how these effects vary with the hydrodynamic and geomorphologic characteristics of the coastal environment. This is mostly due to limitations associated with the computational complexity in simulating field conditions and the availability of *in situ* data in such energetic coastal conditions.

Study Site

The study site is the Portuguese sandy coastal stretch of Cova-Gala (Figure 1), critical for erosion-flooding risks despite the coastal protection with a groin field, seawalls and nourishment. It is subjected to a meso-tidal regime, characterized by a high energy wave climate, with average significant wave height of 2.15 m and a potential sediment drift 1 million m^3yr^{-1}, having high interannual and seasonal variations (Oliveira, Oliveira, and Trigo-Teixeira, 2016).

After the construction of the Mondego river mouth jetties in the 70s, the southern beaches started to erode. This led to the construction of a combined groin and seawall defense scheme in the maritime front of Cova-Gala in the late 70s to intercept the southward directed predominant littoral drift (Figure 1.b). The groin field consists of 5 groins (G1 to G5), four with 100 m length and a fifth southern one with length of 150 m. The seawalls, at the backshore of three of the four cells, have a crest height of approximately 9 m above the zero of the nautical vertical chart datum (CD). Furthermore, the erosion-flooding risks are aggravated by the overall sediment deficit in the Portuguese West Coast, the dredging operations in the Mondego river mouth, the extension of the north jetty (2008-2010), and the sea level rise. This is particularly troublesome during extreme maritime events, when spring tides are combined with meteorological surge and high waves to cause primary dune overwashing and the lowering of the beach in front of the seawalls (Oliveira, Oliveira, and Trigo-Teixeira, 2016).

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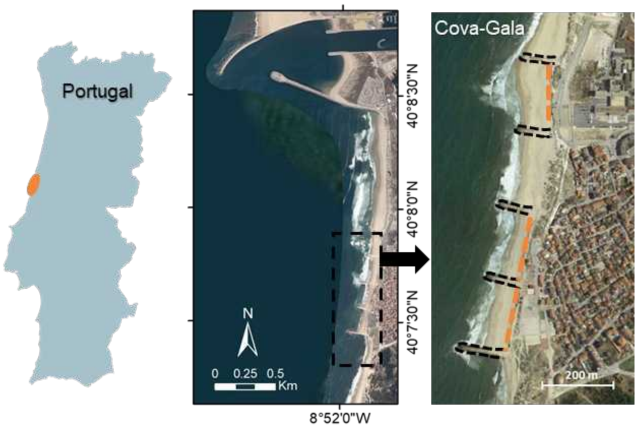

Figure 1. (a) Location of the study site in the Portuguese West Coast and satellite view of the Mondego river mouth and Cova-Gala. (b) Detail of the existing Cova-Gala defense scheme. Image: ESRI Basemap.

This paper applies the XBeach model to investigate the sediment dynamics and the morphological evolution of the study site from August 2018 to February 2019. This is possible due to the availability of an unusually high amount of *in situ* topo-bathymetric data for this energetic coastal site. These data, which covers a wide range of spatial and time scales, result from recent systematic and high frequency surveys.

The morphological response is assessed for a sequence of hydrodynamic conditions: a period of average conditions followed by a period of synoptic conditions. This last period started with a storm followed by typical conditions. The main goal is the assessment of the model performance in a site with a high sediment dynamics for the scenarios: (i) a long period of time; (ii) a two-timescale combined approach to simulate longer periods of time; and (iii) different beach backshore typologies, dune and seawall. The effect of data assimilation during the XBeach application and the influence of the 2D processes in the beach morphological evolution (2DH *vs.* 1D-profile modelling) in the presence of these types of beach backshore are also assessed.

METHODS

The monitoring-modelling approach used in this paper is based on hydrodynamic and topo-bathymetric data collected for the study site from August 2018 to February 2019. The XBeach model was used to simulate: the hydro-morphological evolution of a topo-bathymetric cross-shore profile, in 1D mode; and the hydro-morphological evolution of the overall active zone of the study site in 2DH mode, based on a digital terrain model (DTM) built from a topo-bathymetric area-survey performed annually. Synoptic wave and sea level data were used as the hydrodynamic forcing and a sediment median diameter of 0.30 mm was considered.

The two-layer non-hydrostatic latest version of the process-based numerical model XBeach was used (Roelvink *et al.*, 2018), considering the model parameters recommended by the authors. This wave-resolving model computes both short and long waves (including short wave runup and overwashing) and the processes of wave diffraction and reflection, relevant in the model application to a structure-controlled beach.

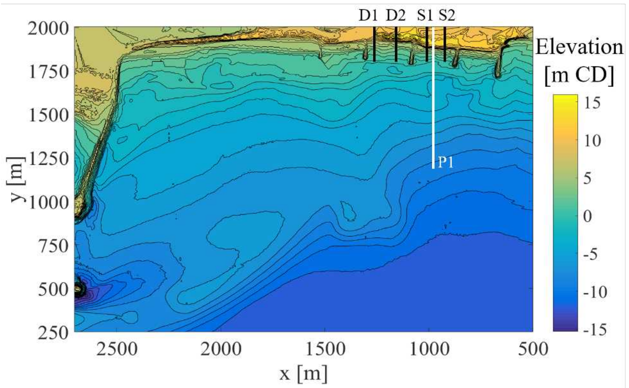

Figure 2. Digital terrain model of the study site in 01.08.2018. Local system origin coordinates in PT-TM06/ETRS89: X=-64229.64 m, Y= 50379.29 m. Location of the monitored topo-bathymetric profile P1 and topographic profiles D1, D2, S1 and S2.

Topo-bathymetric Data

A DTM of 01.08.2018 was generated (Figure 2) using the topo-bathymetry of a large area of the study site, obtained from the Portuguese Environment Agency COSMO coastal monitoring program (https://cosmo.apambiente.pt/). This survey was complemented for deeper water, out of the active zone, with data from topo-bathymetric profiles surveyed by the Figueira da Foz Port Administration (APFF, S.A.), in the scope of the Environmental Monitoring Plan of the Port Maintenance Dredging. The topo-bathymetries of the cross-shore profile P1 (Figure 2), of 15.11.2018 and of 04.02.2019, were also obtained from the COSMO program.

The topographies of the four cross-shore profiles D1, D2, S1 and S2 were obtained during two field campaigns in the scope of the MOSAIC.pt research project (http://mosaic.lnec.pt/). Profiles D1 and D2 are located in cell 2, limited by a natural dune at the backshore, and profiles S1 and S2 are located in cell 3, limited by a seawall. The profiles were surveyed during the low tide of: 04.02.2019, a topographic survey performed by GNSS-RTK; and 11.02.2019, a drone survey at a flight altitude of 50 m.

Hydrodynamic Data

The hindcast wave time series was obtained from the Puertos del Estado dataset for the SIMAR point 1044060 (40ºN 9ºW), at -37 m CD offshore of the study site. The time series, which revealed a good agreement with the Hydrographic Institute data (http://www.hidrografico.pt/m.boias) in several buoy locations for the study period, was transferred through numerical modelling to -12 m CD, corresponding to the sea side longshore boundary of the XBeach computational domain. The sea level time series is from the University of Lisbon for Figueira da Foz (https://webpages.ciencias.ulisboa.pt/~cmantunes/hidrografia/hidro_mares.html) which is validated with the Figueira da Foz tide gauge.

Conceptual Model

The conceptual model for the XBeach application is outlined in Figure 3. The synoptic waves, sea level and surveyed data were considered, as well as the modelling viability in terms of computational load. The morphological response of the study

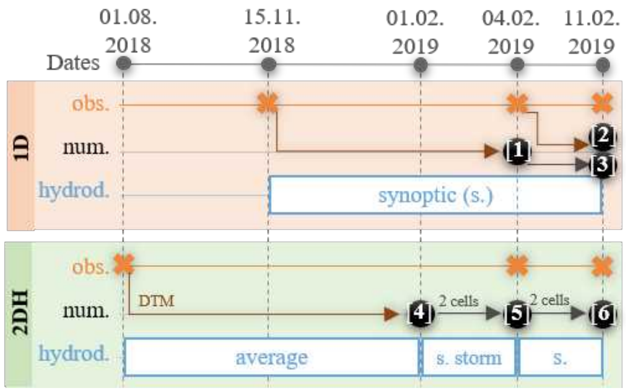

Figure 3. Scheme of the conceptual model adopted for the XBeach application.

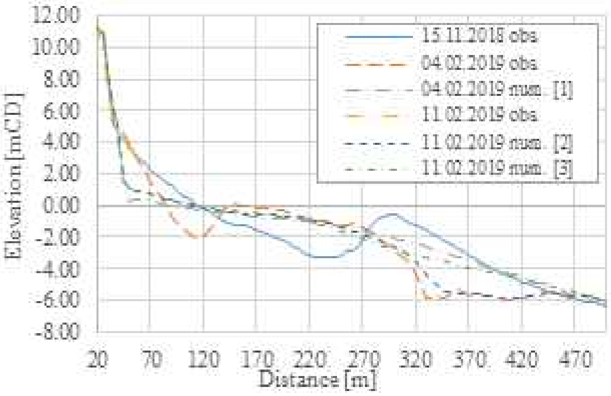

Figure 4. Morphological evolution of P1 (cell 3) from 15.11.2018 to 11.02.2019: observed and numerical profiles in the 1D simulation approach.

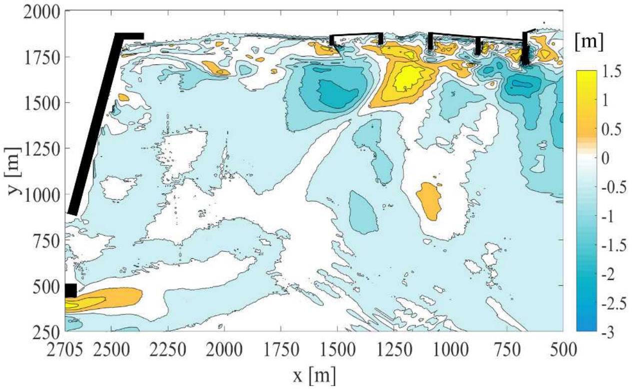

Figure 5. Morphological evolution between 01.08.2018 and 01.02.2019 (morfac 60): elevation differences. Negative values show erosion.

site was assessed for the following periods: (i) 01.08.2018 to 01.02.2019 – six months of typical wave and sea level conditions, with wave average values Hs=2.00 m, Tp=12.14 m, Dir=304ºN and SL=2.23m; followed by (ii) 01.02.2019 to 04.02.2019 – a three days storm event, called storm Helena, during which the atmospheric pressure dropped to 993.3 hPa, with high winds and a maximum offshore wave height of 14.80 m combined with a sea level ranging from 1.10 to 3.30 m CD; and (iii) 04.02.2019 to 11.02.2019 – a post-storm seven days period of typical maritime winter wave conditions with spring tides of 3.55 m CD.

Two modelling approaches using both observed (obs.) and numerical (num.) topo-bathymetric data were considered, as schematized in Figure 3: the profile evolution simulated in 1D and the area evolution simulated in 2DH mode, in which [#] designates the numerical output.

The 1D approach consisted in simulating: (i) the evolution of profile P1 observed in 15.11.2018 to obtain a numerical P1 in 04.02.2019 [1]; (ii) the evolution of P1 observed in 04.02.2019 to obtain a numerical P1 in 11.02.2019 [2]; and (iii) the evolution of [1] to obtain a numerical P1 in 11.02.2019 [3]; all forced with the respective hourly synoptic hydrodynamic conditions.

The 2DH approach consisted in simulating: (i) the evolution of the complete DTM in 01.08.2018 to obtain a numerical DTM in 01.02.2019 [4], after six months of average conditions as the hydrodynamic forcing and a morphodynamic acceleration factor (morfac) of 60; (ii) the evolution of sedimentological cells 2 and 3 in [4], between the groins G2 and G4 of the Cova-Gala defense scheme (Figure 1), to obtain a numerical 2 cells DTM in 04.02.2019 [5], forced with the hourly synoptic hydrodynamic conditions of the storm Helena; and (iii) the evolution of [5] to obtain a numerical 2 cells DTM in 11.02.2019 [6], forced with the hourly synoptic hydrodynamic conditions.

RESULTS

The measured topo-bathymetry of P1 and its morphological evolution resulting from the 1D approach are shown in Figure 4. The results show that: (i) from 15.11.2018 to 04.02.2019, erosion occurred in the seawall toe and in the beach face up to 100 m from the seawall. In the following 140 m, a submerged bar was formed, followed by a significant erosion of the profile seawards, up to 420 m from the seawall. From 04.02.2019 to 11.02.2019, the data available only in the upper beach face show that there was stabilization in this area; (ii) the model overestimated the erosion in the seawall toe in 04.02.2019 but simulated the accretion in the following 140 m rather well [1], resulting in a beach profile smoother than the observed due to the erosion underestimation of the profile seawards. In the following shorter period, the numerical profile [2] is not as smooth as the previous simulation profile [1] but shows the same tendency, overestimating the erosion in the dune toe, followed by accretion in the beach face; and (iii) despite having such different starting morphologies (observed profile and profile [1], respectively), the numerical profiles [2] and [3] show the same evolution up to 300 m from the seawall differing in the following 150 m.

The 2DH morphological evolution of the overall study site from 01.08.2018 to 01.02.2019, using average conditions with morfac 60, is depicted in the elevation differences map in Figure 5. Negative values indicate that erosion occurred at the end of the six months period. The results show that: (i) an erosive tendency is present in the overall study site and is more evident in the southern part, reaching values of 1.5 m in front of G1 and 2 m in

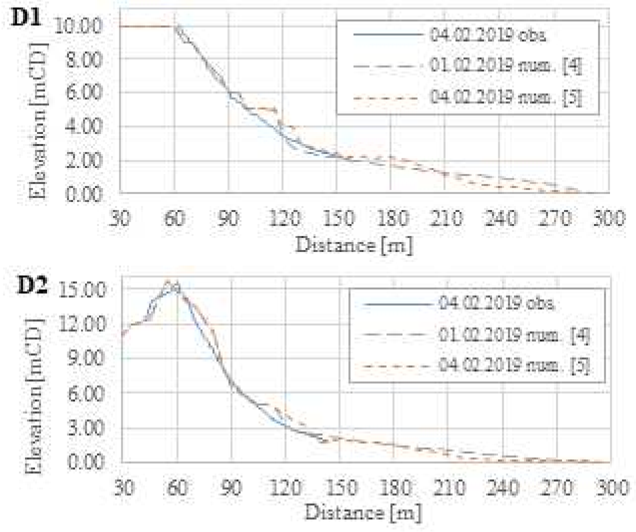

Figure 6. Morphological evolution of the profiles D1 and D2 (cell 2) from 01.02.2019 to 04.02.2019.

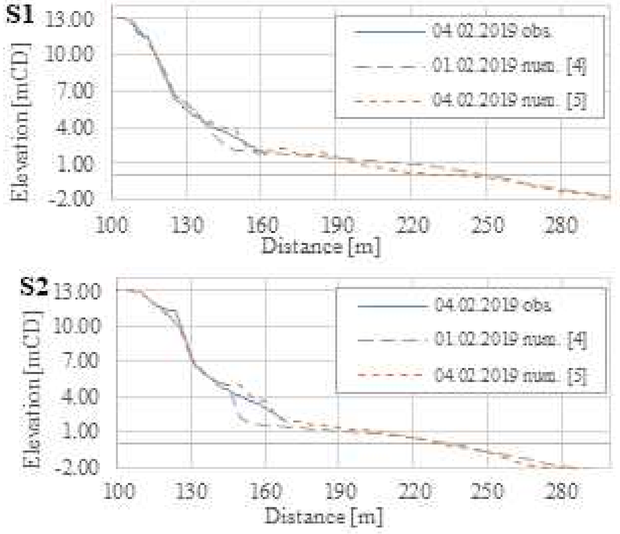

Figure 7. Morphological evolution of the profiles S1 and S2 (cell 3) from 01.02.2019 to 04.02.2019.

front of G5. On the lee side of G5 an erosion hotspot is identified, reaching values of 3 m; (ii) accretion occurred adjacent to the north jetty head and in front of cell 2, reaching values of 1.5 m. Smaller accretion areas are found north of G1 and G5, south of G3 and G4 and further south from G5; and (iii) the 2D sediment fluxes can be identified by the erosion-accretion patterns which indicate the predominance of southward fluxes at different scales.

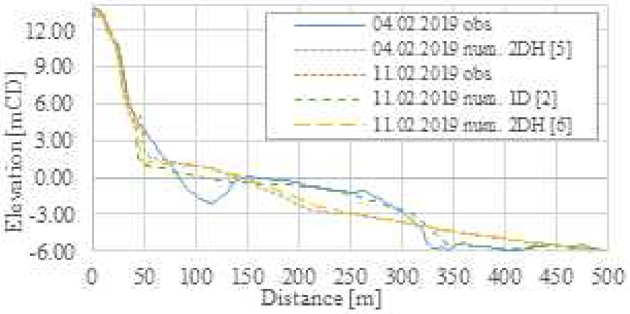

Figure 8. Morphological evolution of P1: observed and numerical profiles in the 1D and 2DH simulation approaches.

The morphological evolution of cell 2 in the 2DH modelling approach during the storm Helena, from 01.02.2019 to 04.02.2019, is represented by the profiles D1 and D2 in Figure 6. The results show that: (i) in both profiles, the post-storm topographies [5] in the upper beach face do not show a good agreement with the measurements; (ii) the simulated dune topography in the cell was not altered above 4 m CD either during the storm or during the six months period simulation, indicating that since 01.08.2018 the dune evolution observed in D2 was due to eolian transport (not accounted by the model); (iii) the lower beach face morphological evolution from [4] to [5] in D1 approximated the numerical six months average topography to the observed in 04.02.2019, as opposite to D2, indicating that the model simulates the storm effect more accurately on the north side of the cell; and (iv) the storm causes the formation of an erosion scarp in the upper part of the beach face in both numerical profiles but only in D1 the formation of a berm in the lower part of the beach face.

The morphological evolution of cell 3 for the same period is represented by the profiles S1 and S2 in Figure 7. The results show that: (i) during the storm, the numerical topography was altered below the seawall toe, 5 m CD; (ii) the morphological evolution from [4] to [5] approximates the average topography to the observed but not as much as in cell 2; (iii) the high erosive volume below the seawall toe that occurred for average conditions [4] is reset during the storm; (iv) the sediment volume mobilized below the seawall toe during the storm is higher in S2; and v) the storm causes the formation of a small numerical berm crest in S1 but not in S2.

The numerical 1D and 2DH approaches were compared to analyze how the model simulates a recovery period using the same synoptic forcing conditions but different modes and different morphologies as the starting point. The morphological evolution of P1 during the post-storm period and the starting morphologies for both approaches are depicted in Figure 8. The results show that: (i) the measured profiles registered a retreated in the seawall toe, where erosion occurred; (ii) the 1D model overestimated the erosion in the seawall toe by 3.5 m and levelled the original beach profile up to 300 m farther from the seawall (iii) the 2DH model overestimated the erosion in the seawall toe in 3.0 m and created a scour hole. This erosion was compensated by accretion in the lower beach profile and there were no changes farther than 200 m from the seawall; and (iv) even though the starting morphologies were very different in the two approaches, the evolution tendency simulated by the model is similar in the upper beach face – extreme erosion in the seawall toe.

DISCUSSION

Regarding the 1D approach results, the onshore bar movement verified in the measured P1 morphological evolution for the first simulation period is the result of a sediment flux that the model, forced with hourly synoptic hydrodynamic conditions, was not able to reproduce. In fact, the results (Figure 4) show that the longer the modelling period is, the more the beach profile is smoothed, converging to the average morpho-hydrodynamic conditions of the simulation. The features of the measured post-storm profile were not modelled correctly because the numerical profile at the beginning of the storm was smoothed by several weeks simulation time. Data assimilation to estimate initial conditions for the model from field observations is very important to prevent the profile features from being lost by the smoothing effect of long simulation periods. In a seawall profile, the model repeatedly over-estimates the erosion in the seawall toe, in the upper beach face and for distances from 240 to 440 m from the seawall toe. For depths greater than -6 m CD, the model shows stability and a good agreement with the measured data for both the 1D and the 2DH approaches.

The modelled six months 2DH morphological evolution depicts an overall erosion scenario (Figure 5), intrinsic of the study site energetic hydrodynamic conditions, as characterized by Oliveira, Oliveira, and Trigo-Teixeira (2016). The mean wave direction obliquity of 25º (clockwise, with respect to the cross-shore direction) that causes the predominance of a southward directed sediment flux at different scales, explains the critical erosion predicted near the southern boundary as the jetties sheltering effect do not reach this area. The stability of the dune and safety of the south Cova-Gala frontage has been an issue, leading to several local interventions in the past years. The recent beach nourishments seawards of G1, with the material dredged from the Mondego river mouth, tend to change the local sediment fluxes, in response to the forcing hydrodynamics, until a new bottom equilibrium condition is reached under average conditions. This explains the final erosion-accretion pattern in the area resultant from the 2DH model restoring the equilibrium during the six-month period (01.08.2018 – 01.02.2019) of average hydrodynamic forcing.

The medium-term evolution of a cell with a dune backshore (Figure 6), rather than a seawall backshore (Figure 7), is more accurately simulated by the model. For the 2DH approach, the model can simulate the storm event using hydrodynamic synoptic data more accurately than with the 1D mode and is even capable of reproducing a post-storm berm crest in the north side of cells 2 and 3. During the recovery period, seven days of synoptic hydrodynamic forcing with average wave energy, the tendency of the model to over-estimate the erosion in the seawall toe and to smooth the overall numerical profile is evident in both the 1D and 2DH approaches; the 1D approach maintains the observed profile features assimilated with the observed data available at the beginning of this period. The lack of hydrographic data for the breaking zone, which is a challenge to gather, in the end of the period makes it difficult to validate the complete post-storm profile, but it seems that the model results for the erosion at the seawall toe are not in agreement with the topographic measurements. In addition, it should be emphasized that it remains unknown the role of the eolian transport in this process of profile recovery.

CONCLUSIONS

The morphological evolution of the heavily protected Cova-Gala coastal frontage (West Portugal) was assessed through field campaigns and numerical modelling, with XBeach, for a period of average hydrodynamic conditions, followed by an energetic storm event and its recovery period. The overall medium-term erosion scenario depicted by the results is characteristic of a southward directed sediment flux in a site where the average wave energy is high and sediment supply is low, creating critical erosion hotspots at different scales. The model performance for a storm event is better in the 2DH mode than 1D mode, and the beach face morphological evolution of a dune backshore typology beach is more accurately modelled than that of a seawall backshore typology. Although field data in the nearshore may be scarce and the model can run on average representative conditions to provide morphological evolution tendencies, data assimilation of the geometrical features of the actual morphology from field observations is crucial for more realistic model results.

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LITERATURE CITED

Oliveira, J.N.C.; Oliveira, F.S.B.F., and Trigo-Teixeira, A.A., 2016. Coastline evolution south of the Mondego river inlet: modelling the impact of the extension of the north jetty. *Proceeding, 4th Hydrographic Institute Scientific Journeys*, 245-248.

Roelvink, D.; Reniers, A.; Dongeren, A.; Vries, J.T.; McCall, R., and Lescinski, J., 2009. Modelling storm impacts on beaches, dunes and barrier islands. *Coastal Engineering*, 56, 1133-1152.

Roelvink, D.; McCall, R.; Mehvar, S.; Nederhoff, K., and Dastgheib, A., 2018. Improving predictions of swash dynamics in XBeach: The role of groupiness and incident-band runup. *Coastal Engineering*, 134, 103-123.