The effect of dune morphology longshore variation in the beach-dune system resilience

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Abstract: The present study consists on the analysis of the effect of the longshore variation of the frontal dune morphology in the beach-dune system morphodynamics during erosion events. Despite the predominance of the cross-shore component of the coastal processes under storm conditions, it is important to understand how the longshore gradient of such processes can affect the cross-shore component. The lack of field or laboratory data is an obstacle to the understanding of the underlying physics. Thus, this investigation is developed with a 2DH process-based numerical model. The morphology of the study zone is simplified in order to limit the complexity of the underlying physics and to be able to identify the driving processes more clearly. Initially, the bathymetry is uniform and only the frontal dune height varies alongshore. However, in time, as the dunes erode, only the topography above the foreshore becomes non-uniform, despite the volume of sediment extracted from the dune face which is transported seaward being higher for the highest dunes. Such sediment is stirred by the longshore current to the adjacent areas in front of the lowest dunes protecting these against erosion.

Key words: non-uniform beach, dune, erosion, submerged bar, morphodynamics.

1. INTRODUCTION

Beach-dune systems are the most important natural defences in the sea-land interface. Their episodic erosion, due to combined wave and surge action during maritime storms, can have a high risk, causing damage, or even loss, of infrastructures and natural environments. Therefore, it is important to capture the physics involved and, thus, to forecast accurately the impact of these episodes in order to provide credible information for suitable protection and management.

Coastal dune resilience to maritime storms has been mostly assessed through the application of cross-shore morphodynamic numerical models because, under such conditions, the cross-shore component of the coastal processes is predominant. These models can be empirical models, like the Duner model (Oliveira, 2012a, 2012b, 2013); semi-empirical models, like the SBeach model (Larson and Kraus, 1989); and deterministic models, also known as process-based models, like the Litprof model (DHI, 2008) and the XBeach model (Roelvink *et al.*, 2009). However, in order to improve the accuracy of beach morphological response predictions under extreme conditions of wave energy and surge, it is important to understand how the longshore gradient of such processes can affect the cross-shore component.

The objective of the present study is to assess the effect of the longshore variation of the frontal dune morphology in the beach-dune system morphodynamics, in particular, in the resilience of the beach-dune system as a whole, during erosion events. The lack of field or laboratory data (field observations and experiments that include the longshore direction are very rare; knowledge on dune erosion is mainly based on large scale flume experiments) is an obstacle to the understanding of the underlying physics. Therefore, this investigation is developed with a credible 2DH (two dimensional, horizontal) process-based numerical model, the XBeach model. The results obtained were compared with the results of the 1D (one dimensional, cross-shore) simulation in order to identify the alongshore sediment transport gradient impact on the morphological evolution.

2. DATA AND METHOD

2.1. Morpho-sedimentologic conditions

The morphology of the study zone was simplified in order to limit the complexity of the underlying physics and to be able to identify the driving processes more clearly. The study zone covers a coastal area with 3500x1000 m^2 (longshore and cross-shore extensions, respectively). The initial (t = 0 s) morphologic conditions were based on a representative cross-shore profile located in the Ancão spit, near Faro, Algarve, region where dune notching can be observe, as illustrated in Figure 1. The profile geometry was obtained by joining the depth, obtained through a hydrographic survey, to the foreshore-berm-dune elevation, obtained through a LIDAR topographic survey. The initial bathymetry and topography of the foreshore and berm were considered uniform alongshore for the total study area. Only the frontal dune height varied in the sequence of the five longshore stretches which compose the study zone. In the lateral and central stretches, with 1000 and 500 m of alongshore extension, respectively, the dune height was 9 m above the nautical Chart Datum (CD), presently at 2.15 m below mean sea level (MSL) in this coastal region (Figure 2). In the intermediate stretches, with

500 m of alongshore extension, the dune height was 6 m above CD (Figure 2). The x and y coordinates of the uniform Cartesian grid applied were aligned with the cross-shore and longshore directions, respectively. It was used the grid spacing dx=1 m and dy=20 m.

The profile sediment grain size was characterised by the statistic parameters median grain diameter, D50=0.5 mm, and 90th percentile, D90=0.8 mm, based on the results of the grain size analysis of sediment samples near the location of the representative cross-shore profile. The sediment density was 2.65.

Fig. 1. Dune notch in the coast of Algarve, Portugal.

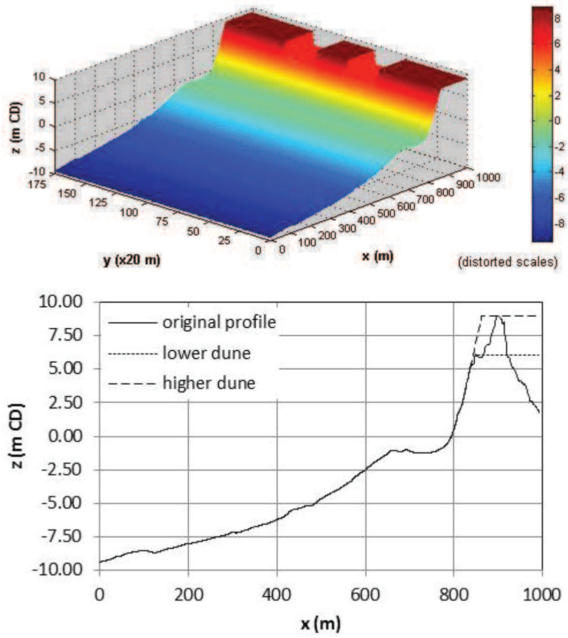

Fig. 2. Initial topo-hydrography: profiles (below) and 2DH (above).

2.2. Hydrodynamic storm conditions

The wave and sea level (η) series considered in the simulations are based in the 50-year return period maritime storm parameters in front of Ancão spit. For the storm surge elevation (residual obtained from the difference between the observed sea level and the predicted tidal level), it was applied the 50-year return period surge, 0.9 m, calculated as described by Sancho *et al.* (2012) and considered constant during the storm. The maximum sea level applied at the offshore boundary, 4.42 m CD, resulted from of the sum of the mean high water spring (MHWS) tidal level determined at Faro, 3.52 m CD, with the surge (Figure 3). The duration of the simulated storm was 24 hours. The maximum significant wave height and wave peak period associated to a 50-year return period at the offshore of the Ancão spit are $Hs_{max} = 7.00$ m and Tp = 12.5 s, respectively, according to the same authors (Sancho *et al.*, 2012). These wave parameters, together with a mean wave direction correspondent to an angle of incidence of 30° with the normal to the shore, were considered constant in the boundary conditions time series at the incoming wave boundaries of the 1D and 2DH simulations.

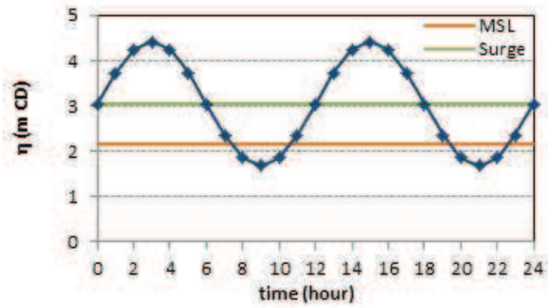

Fig. 3. Time varying offshore sea level boundary condition.

2.3. Morphodynamic numerical model

The XBeach (eXtreme Beach behaviour) model (Roelvink *et al.*, 2009; Roelvink *et al.*, 2010) can simulate the main processes which occur in the four regimes of maritime storm impact described by Sallanger (2000): swash, collision, overwash and inundation. However, only the first two were considered in the present case study.

It solves coupled 2DH equations for wave propagation, flow, sediment transport and bottom changes, for varying (spectral) wave, flow and sediment concentration boundary conditions. The main governing equations are:

a) The time dependent short wave action balance on the scale of wave groups. The directional distribution of the short wave action density is taken into account in the model, but the frequency distribution is reduced to a single representative peak frequency, assuming a narrow banded incident spectrum.

b) The roller energy balance. It is coupled to the wave-action/energy balance where dissipation of wave energy serves as a source term for the roller energy balance. Similar to the wave action the directional distribution of the roller energy is taken into account whereas the frequency spectrum is represented by a single mean frequency.

c) The shallow water momentum and mass balance equations, to solve the surface elevation and flow, including infragravity waves and unsteady wave induced currents. To include short wave induced mass fluxes and return flows in shallow water, the Generalized Lagrangian Mean (GLM) formulations, without Coriolis forcing, are used in the model.

d) The sediment transport rates formulations, in which the sediment concentrations in the water column are solved using a depth-averaged advection-diffusion equation with a source-sink term based on an equilibrium sediment concentration equation.

e) The avalanching formulation in order to simulate dune slumping.

f) The continuity equation to solve the bed level change due to sediment transport rate gradients.

The model uses a staggered grid, in which conservative quantities (water level, bed level, etc) are calculated in cell centres and fluxes (velocities, sediment transport, radiation stress gradients, etc) are calculated in cell interfaces.

Boundary conditions ensure that the model produces only one out of an infinite set of possible answers.

3. RESULTS AND DISCUSSION

The 1D simulations performed for each case, lower dune (LD) and higher dune (HD), reveal that the dune crest retreat was significantly higher in the LD than in the HD (Figure 4) and that the sand volume eroded from the initial foreshore (between 1.68 and 4.42 m CD) and above the maximum storm surge level (MSSL), and then transported seaward, was 15% higher in the HD than in the LD (Figure 5). In result, the filling of the wide planar stretch of the surf zone exhibited at approximately -1 m CD in the pre-storm profile (see Figure 4), was greater for the HD (Figures 4 and 6). The most likely explanation is that the larger retreat of the LD (when comparing with the retreat of the HD) leads to a simultaneous larger retreat of the foreshore, and, consequently, smaller erosion at the upper part of the profile submitted to wave action.

In the 2DH simulation the profile evolution for each case, LD and HD, is affected by the morphological evolution of the adjacent zone located at the incoming wave side. The dune crest retreat is not as large as in the 1D simulations (Figure 4). The sand volume eroded from the foreshore and above MSSL, and then transported seaward, was 17% higher in the HD than in the LD (Figure 5), approximately the same correlation as in the 1D simulations. However, its magnitude was reduced by 25% (comparing with the 1D simulations), which is in correlation with the smaller retreat of the dune crest. It is known that under storm conditions dune erosion is dominated by wave group generated long waves. A possible explanation for the smaller impact of the storm in the 2DH simulation is the effect of short wave spreading on long waves, but that must be further investigated.

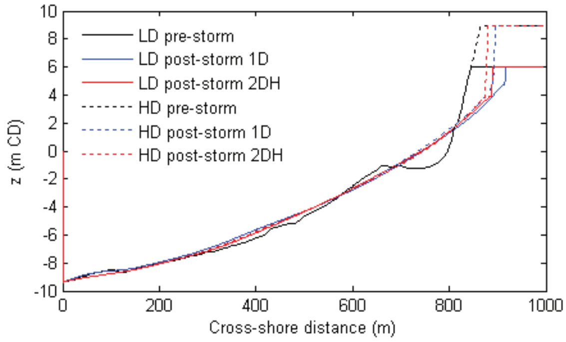

Fig. 4. Profile evolution for the HD and LD cases in the 1D and 2DH simulations.

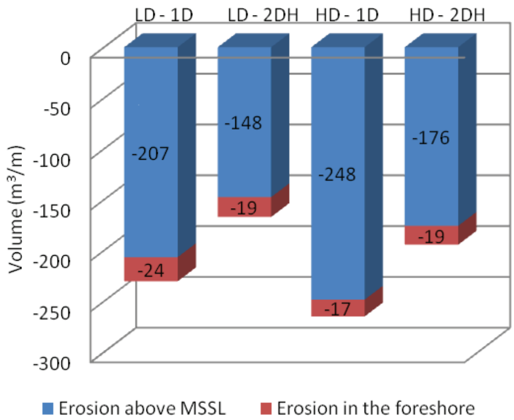

Fig. 5. Erosion volume for the HD and LD cases in the 1D and 2DH simulations.

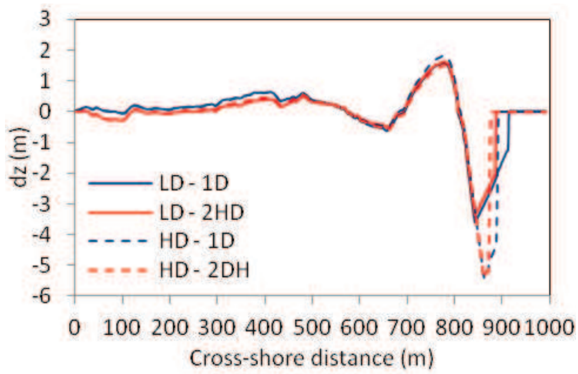

Fig. 6. Variation of the profile elevation (z coordinate) for the HD and LD cases in the 1D and 2DH simulations.

Despite the erosion volume of the HD being higher than the erosion volume of the LD for the 2DH simulation, the change in the profile elevation (z coordinate), shown in Figure 6, reveals that the erosion in the lower foreshore and the deposition in the surf zone are very similar in both cases, LD and HD. Therefore, it can be concluded that part of the volume eroded from the HD was stirred by the longshore current and deposited in the LD surf zone. This redistribution of sediment in the longshore direction results in protection of the LD by the HD against the storm impact.

4. CONCLUSIONS

The objective of the present study was to assess the effect of the longshore variation of the frontal dune morphology in the beach-dune system morphodynamics, in particular, in the resilience of the beach-dune system as a whole, during erosion events. The lack of field or laboratory data is an obstacle to the understanding of the underlying physics. Therefore, to achieve the objective of the study, a credible 2DH (two dimensional, horizontal) process-based numerical model, the XBeach model, was applied to a simplified morphology, established in order to limit the complexity of the underlying physics and to be able to identify the driving processes more clearly, and the results obtained were compared with the results of the 1D (one dimensional, cross-shore) simulation.

This investigation allowed to conclude the following:

- the alongshore variation of the dune height causes a greater extraction of sediment volume from the frontal dune face at the highest dunes and a larger retreat (landward displacement) of the dune crest at the lowest dunes;
- the sediment eroded at the highest dunes increases the resilience of the beach-dune system as a whole because it is later redistributed by the longshore current and deposited in the surf zone in front of the lowest dunes, thus, protecting them against the storm impact;
- despite the predominance of the impact of the erosion processes cross-shore component during storm events, the oblique wave incidence damps alongshore variations of the surf zone bathymetry, turning it uniform alongshore;
- the 2DH simulation produces longshore effects that result in a smaller, about 25% less, dune erosion volume than the 1D simulations. The most likely explanation is the effect of short wave spreading on long waves, but that must be further investigated, particularly because such predictions are not on the safe side for engineering studies.

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