Modelling beach morphological changes during episodic erosion-recovery events: preliminary results

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Abstract: Episodic and seasonal beach-dune system erosion, unlike long-term erosion, are, in general, followed by natural beach-dune recovery. This study, developed based on numerical modelling, is focused on the wind driven waves onshore and offshore induced sediment fluxes and resulting beach-dune morphological evolution, particularly on the underlying physics not yet fully understood, during episodic events of erosion-recovery. The objective is to improve the prediction capacity of the short to medium-term morphodynamic numerical model XBeach, particularly in what concerns the beach recovery phenomenon, and thus contribute to its credible application.

Key words: beach erosion, beach recovery, episodic event, physical processes, morphodynamics.

1. INTRODUCTION

Episodic and seasonal beach-dune system erosion are cyclic phenomena characterized by a decrease of sediment volume in the beach and dune zones, which result in the retreat of topographic lines like the dune vegetation line and the mean sea level line. Unlike long-term erosion (which corresponds to the exact definition of erosion, despite the accepted broader use of the term), they are, in general, followed by natural beach-dune recovery. These phenomena, usually associated to sea storm events that occur during the maritime season (between October-March for the Portuguese coast), can have a devastating effect in beach-dune systems, placing people, infrastructures and natural environments in danger.

The literature reveals that the phenomenon of dune erosion under sea storm conditions started to be studied in the late 1960s, based on theoretical or experimental approaches (Edelman, 1968; van der Meulen and Gourlay, 1968). Since then, many studies have been undertaken and the approaches have been improved, not only due to the accumulation and deepening of the knowledge but also due the advances of the computing science, which allowed developing numerical models as an analytical tool to investigate the phenomenon (van de Graaff, 1977; Vellinga, 1982; Fisher and Overton, 1984; Kriebel and Dean, 1985; Overton and Fisher, 1988; van de Graaff, 1986; Larson and Kraus, 1989; Sallanger, 2000; Larson *et al*., 2004; Roelvink *et al*., 2009; Oliveira, 2012a, 2012b, 2013).

In opposition, despite the existence of empirical knowledge on the post-storm beach-dune system recovery phenomenon, few analytical studies which analyze the interaction between the hydrodynamic and the geomorphologic processes have been conducted so far. The first study on dune recovery based on field observations was developed by Carter *et al*. (1990).

In brief, the phenomenon of post-storm beach-dune system recovery starts with the onshore transport of the sediment that was accumulated in the form a submerged bar during the beach-dune erosion process. The sediment is transferred from the bar towards the beach foreshore (beach face) by the low energy hydrodynamic forcing conditions (wind driven waves under calm conditions). Then, due to the tide induced sea level variation and the wind action (aeolian transport) the sediment is accumulated between the mean high water springs and the beach scarp leading to the formation of an echo dune. Once the scarp slope is filled and lying below the angle of repose, vegetation growth accelerates the dune recovery process. The rebuilding of the seaward dune face depends largely on the beach foreshore-berm-dune sediment exchanges, which are determined by a wide range of environmental parameters, such as sediment availability, moisture content and wind conditions.

This study, based on a numerical approach, is focused on the physics, not yet fully understood, involved in the offshore and onshore sediment fluxes and resulting beach-dune system morphological evolution, induced by wind driven waves, during short to medium-term episodic events of erosion-recovery. The objective of the study is to test and improve the capacity of a numerical model, the XBeach, to simulate the physical processes which cause the first phase, described above, of the post-storm beach recovery phenomenon.

2. DATA AND METHOD

2.1. Storm conditions

The morphologic initial conditions were based on a representative cross-shore profile located in the Ancão spit, near Faro, Algarve. The profile elevation, relative to the nautical Chart Datum (CD), presently 2.15 m below the mean sea level (MSL) for this location, resulted from joining the depth obtained from a hydrographic survey to the dune elevation obtained, in a close date, from a LIDAR topographic survey. For the spatial resolution of the model it was considered a uniform cross-shore grid spacing with dx=1.00 m.

The 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.

The wave and sea level series considered in the simulation correspond to the 50-year return period maritime storm parameters in front of Ancão spit (Table I). 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. The duration of the 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 Hsmax = 7.00 m and Tp = 12.5 s, respectively, according to the same authors (Sancho *et al.*, 2012). These wave parameters together with normal wave incidence (same alignment as the cross-shore profile) were considered constant along the storm.

2.2. Post-storm conditions

The geomorphologic initial conditions were the post-storm conditions, that is, the initial profile of the recovery simulation was the final profile of the storm simulation.

The wave and sea level series considered are representative of the local calm sea state conditions (Table I). The surge was considered null and the maximum sea level applied at the offshore boundary, 2.76 m CD, resulted from considering the mean high water (MHW) tidal level determined at Faro. The wave conditions were determined based on the wave data of the WAVEC buoy, deployed at 93 m depth in a location with geographic coordinates 36° 54’ 17’’ Latitude (N) and 7° 53’ 54’’ Longitude (W), in front of Faro. Based on the analysis of the data for the period Sep/1986-Dec/2000, from Costa *et al*. (2001), and for the period Jan/1998-Dec/2007, from Capitão *et al*. (2009), the significant wave height and wave peak period selected to represent calm conditions were Hs = 1 m and Tp = 7 s, each value correspondent to the upper limit of the most frequent class of occurrence. The waves were considered with normal incidence in the simulation.

2.3. Morphodynamic numerical model

The XBeach (eXtreme Beach behaviour) model (Roelvink *et al*., 2009) is a 2DH (two dimensional, horizontal) process-based morphodynamic numerical model that 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 (BC), which ensure that the model produces only one out of an infinite set of possible answers.

Table I. Hydrodynamic conditions.

	Hs (m)	*Tp (s)*	*Surge (m)*	*Tide*	*Duration (day)*
Erosion	7	12.5	0.9	MHWS	1
Recovery	1	7	0	MHW	10

3. RESULTS AND DISCUSSION

3.1. Modelling storm-induced erosion

The results of the simulation show that during the storm event the beach-dune profile was subjected to the extraction of 141 m^3/m of sand above 2.25 m CD, causing a retreat of 49 m of the dune crest (Figure 1). Such sand was transported seaward by the undertow current an accumulated in the wide planar stretch of the surf zone exhibited at approximately -1 m CD. In an initial stage (see profile after 6 hours), this sand flux formed a submerged bar, which seaward face continued to grow until the end of the storm. After 24 hours, the profile was filled between the vertical levels -1 and 2.25 m CD, within a horizontal cross-shore distance of about 117 m. This sand flux had the effect of smoothing out the slope of the pre-storm submerged profile.

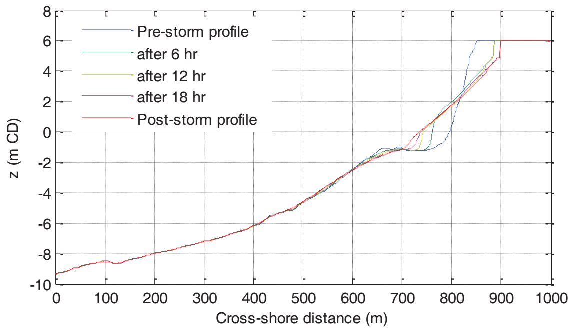

Fig. 1. Simulation of the storm impact.

3.2. Modelling post-storm recovery

The results of the simulation indicate that the model is capable of transferring sand from the surf zone to the foreshore (Figure 2). In this case, since the surge was null, the tide induced sea level varied between 1.54 and 2.76 m CD at the offshore boundary. The onshore sediment flux accumulated at the foreshore stabilized after 5 days, when the exchanged volume reached approximately 30 m^3/m (Figure 3).

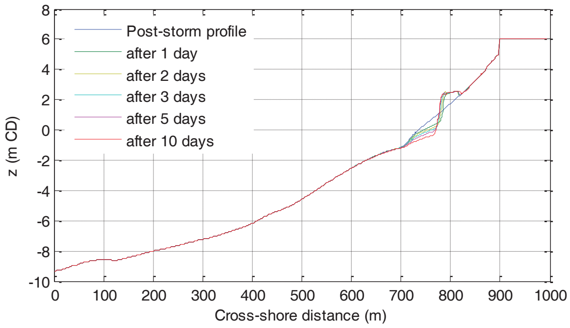

Fig. 2. Simulation of the beach recovery.

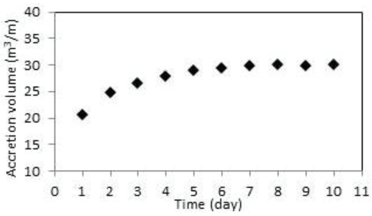

Fig. 3. Evolution of the accretion volume at the foreshore.

3.3. Underlying physics

It was considered, based on previous studies (Grasso *et al.*, 2011), that the intra-wave sediment transport caused by the wave asymmetry and skewness is the primarily process responsible for the onshore sediment transport. Under storm conditions intra-wave sediment transport due to wave asymmetry and wave skewness are expected to be relatively minor compared to long-wave and mean current contributions.

The wave asymmetry and skewness, parameterized as a function of the Ursell number, U_r, as follows:

$$S_k = \frac{0.79}{1+\exp\frac{-0.61-\log U_r}{-0.35}}\cos\left(-\frac{\pi}{2}+\frac{\pi}{2}\tanh(0.64/U_r^{0.6})\right)$$
$$A_s = \frac{0.79}{1+\exp\frac{-0.61-\log U_r}{-0.35}}\sin\left(-\frac{\pi}{2}+\frac{\pi}{2}\tanh(0.64/U_r^{0.6})\right) \quad (1)$$

were considered in the depth average advection-diffusion equation (Galappatti and Vreugdenhil, 1985), through the representative velocity, u_{reps}. This velocity is equal to the sum of the current flow velocity, u^E, with the advection velocity, u^a, from wave skweness and asymmetry, calculated as follows:

$$u_{reps} = u^E + u^a \quad (2)$$

$$u^a = \gamma_{ua}(S_k - A_s)u_{rms} \quad (3)$$

where γ_{ua} is a free parameter which determines the magnitude and direction of net sediment transport. This parameter was considered equal to 1 in the beach recovery simulation and null in the storm simulation.

To calculate the sediment equilibrium concentration, C_{eq}, in the beach recovery simulation, it was applied the van Thiel-van Rijn (van Rijn, 2007) formulation, which reads as follows:

$$C_{eq} = \frac{A_{sb}}{h}\left(\sqrt{(u^E)^2+0.64u_{rms,2}^2}-u_{cr}\right)^{1.5} + \frac{A_{ss}}{h}\left(\sqrt{(u^E)^2+0.64u_{rms,2}^2}-u_{cr}\right)^{2.4} \quad (4)$$

where A_{sb} and A_{ss} are the bed load and suspended load coefficients (Soulsby, 1997), respectively; h is the depth; u^E is the Eulerian velocity (the average velocity of the short-wave in a fixed position); u_{cr} is the threshold velocity; and $u_{rms,2}$ is the near-bed short-wave orbital velocity obtained from the wave-group varying wave energy including wave breaking induced turbulence, calculated as follows:

$$u_{rms,2}^2 = u_{rms}^2 + 1.45k_b \quad (5)$$

where u_{rms} is the instantaneous short-wave orbital velocity and k_b accounts for the breaking induced turbulence.

For the storm simulation, the sediment equilibrium concentration, C_{eq}, was calculated using the frequently applied Soulsby-van Rijn formulation (Soulsby, 1997), in which the sediment is stirred due to mean (short-wave averaged) and infragravity (wave group) velocities.

Another factor that plays a significant role in the berm formation during the accretion phase is the permeability of the beach. For this reason, the groundwater flow process was considered in the beach recovery simulation through the application of the principle of Darcy flow. The infiltration was calculated as follows:

$$w = -k_z\left(\frac{dp}{dz}+1\right) \quad (6)$$

where p is the groundwater head and k_z is the Darcy permeability coefficient of the aquifer in the vertical direction. The Darcy permeability coefficient of the aquifer was considered 0.003 m.s^{-1}.

Due to the large duration of the recovery phenomenon, the morphological factor, *morfac*, that speeds up the morphological time scale relative to the hydrodynamic timescale, was considered equal to 10 in the beach recovery simulation. In contrast, for the storm simulation this factor was considered equal to 1.

4. CONCLUSIONS AND FUTURE WORK

This paper describes the preliminary results of a study which objective is to test and improve the capacity of the XBeach model to simulate the physical processes that cause episodic events of beach erosion-recovery. Despite the use of real geomorphologic and hydrodynamic data, there was not enough topo-hydrografic information available for verifying the model. Thus, its application was done in a theoretical perspective, to test the model capacity to simulate the underlying physics of beach-dune erosion and beach-recovery, under hydrodynamic conditions known in advance as inducing each of the two phenomenon.

The results obtained indicate that the model can simulate beach recovery if the processes known so far as the primarily responsible for the onshore transport and the berm formation are considered: wave asymmetry and skewness and groundwater flow. Questions like: how accurately does the model do it, how the accuracy varies with the phenomenon time scale and with the model spatial resolution, how does the phenomenon depend on the geomorphologic features of the beach-dune system (mainly the role of the foreshore slope); are yet to be answered and that can be better investigated using this model.

The next task should be calibrating the model, starting with the waves and following with the sediment transport, a task far from trivial. In the future, the model will be coupled with an aeolian transport model to simulate the formation of the echo dune and thus extend the beach recovery simulations to the time scale of months.

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