Modelling 2DH beach morphodynamics in XBeach: model versions and hydrodynamic modes performance

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Resumo: O modelo numérico XBeach, cada vez mais aplicado na simulação dos complexos processos hidro-morfodinâmicos da zona costeira, tem sido atualizado com várias melhorias ao longo dos últimos anos. Este estudo investiga as implicações da utilização dos modos Surfbeat e Não-Hidrostático das duas versões 2DH mais recentes do modelo, Kingsday (2015) e XBeachX (2018), na modelação da evolução morfológica para um *setup* de referência. São simulados dois dias de evolução morfológica de uma área cuja topo-batimetria uniforme é interrompida pela presença de uma estrutura de defesa costeira transversal, centrada no domínio. O forçamento hidrodinâmico consiste numa onda erosiva regular, sendo as condições hidro-morfológicas consideradas representativas da zona de estudo, Cova-Gala, localizada na zona central da Costa Oeste portuguesa. Os resultados, que demonstram diferentes tendências e padrões de evolução morfológica, são discutidos à luz do conhecimento dos processos contemplados nas respetivas versões-modos do modelo e das suas correlações.

Palavras-chave: beach morphodynamics, erosion, groyne, numerical modelling, XBeach.

1. INTRODUCTION

Many coastal populations are exposed to coastal erosion, wave attack and flooding, mostly due to land use pressure. These hazards tend to aggravate due to the climate change induced sea level rise and expected increase of storm frequency and intensity. There is a need for a better understanding of the complex coastal dynamics and adaptation to climate change as these populations rely on the performance of coastal defence structures for protection.

Morphodynamic numerical models are nowadays critical to predict the complex hydrodynamic and morphological behaviour of the nearshore and improve the effectiveness of coastal protection solutions. The interactions between the hydrodynamic forcing and the sedimentary bottom accounted for in process-based models such as XBeach, allow a comprehensive understanding of the coastal dynamics for simplified or complex local hydro-morphological characteristics, including the influence of the presence of coastal defence structures.

Over the last few years, the numerical schemes and physical formulations implemented in the XBeach model have been improved and new formulations have been included and validated in new releases.

This study investigates the differences and implications of using the Surfbeat (SB) and Non-hydrostatic (NH) modes of the two latest XBeach-2DH versions, Kingsday (2015) and XBeachX (2018), in modelling morphological evolution tendencies for a setup of reference. The hydro-morphological and sedimentological characteristics used in the model setup, as well as the cross-shore defence structure design parameters, are representative of a study site located in the highly dynamic central-west coast of Portugal, Cova-Gala. Two days of morphological evolution were modelled for a hydrodynamic forcing scenario consisting of a simple stationary erosive wave. The objective is to analyse the differences in the morphological evolution patterns obtained for the same conditions, and relate them with the improvements and the processes accounted for in the respective version-mode to better understand how to optimize the implementation of XBeach in morphological evolution modelling.

2. DATA AND METHODS

2.1 Topo-bathymetry and sedimentology

The topo-bathymetric characteristics adopted as the initial morphology of the computational area were based on the representative conditions for Cova-Gala as defined by Oliveira *et al.* (2016). The computational domain, with 800x1100 m^2 (dimensions in the alongshore and cross-shore directions respectively), consists of a uniform grid with a resolution of dx=dy=5 m. The alongshore uniform numerical profile consists of three slopes: 1:77 in the submerged profile, between 12 m below the vertical chart datum reference level (ZH) and ZH; 1:25 in the beach face, between ZH and 4 m above ZH; and 1:3.5 in the frontal dune, between 4 and 14 m above ZH (Figure 1). The domain is limited by a sandy dune at the landwards boundary. At the centre of the domain, the uniform crest level of the 260 m long and 20 m wide groyne is set at 5 m above ZH, and the bottom of the head of the structure is set at 2 m below ZH. The sediment size characteristics representative of the bottom of the study site were considered uniform in the domain: sand with median and 90th percentile diameter d_{50}=0.30 mm and d_{90}=0.50 mm (Oliveira *et al*. 2016).

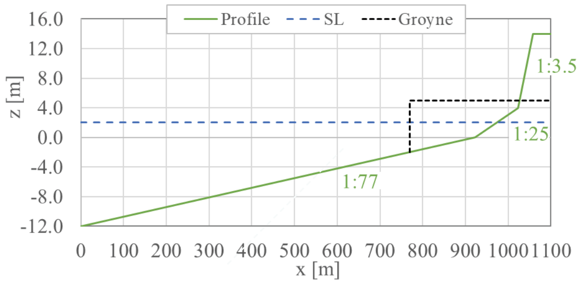

Fig. 1. Morphodynamic model initial bottom configuration: representative beach profile, groyne and sea level (SL).

2.2 Hydrodynamic conditions

A simple stationary erosive scenario was considered during the 48 hours of morphological evolution simulated. The hydrodynamic forcing consisted of a wave with Hs=2.15 m and Tp=11.5 s, the average values characteristic of the study site for the period 1952 to 2010 (Oliveira *et al.*, 2016). A wave angle of 45º of incidence was considered, so that the longshore sediment transport is maximum according to the CERC formulation. These hydrodynamic conditions are considered erosive for the topo-bathymetric characteristics adopted (Oliveira *et al.*, 2016). The mean sea level (SL) was set at 2 m above ZH.

2.3 Numerical modelling

The hydro-morphodynamic model XBeach (Roelvink *et al.*, 2009) was originally developed to assess the natural coastal response to time varying storm and hurricane conditions. By solving the non-stationary shallow water equations, the sediment transport equations, and the continuity equation for the bed update, it can model wave runup, dune erosion, overwashing and breaching. Since its original development, several improvements have been implemented in new releases and it can be applied in three different modes. The Stationary mode solves the wave-averaged equations but neglects infragravity waves. The SB mode solves the short-wave variations on the wave group scale and the associated long waves separately and is the most used when the focus is on swash zone processes and has been extensively validated for the morphological evolution modelling of dissipative beaches. The wave-resolving Non-Hydrostatic mode (NH) computes both short and long waves but with greater computational demand. It combines the non-linear shallow water equations with a pressure correction term and accounts for the wave diffraction and reflection processes. Sandy morphology modelling using the NH mode can be desirable when beach slopes are steeper or when there is a presence of a hard structure. Although this mode was originally developed towards hydrodynamic modelling, the sediment transport formulations have been improved in the latest model version.

Four different version-mode scenarios using a setup of reference were considered (*vd.* Table I): the XBeach *1.22.4867 Kingsday* version was used in simulations 1, SB mode, and 2, NH mode; and the *1.23.5526 XBeachX* version was used in simulations 3, SB mode, and 4, NH mode.

Table I. XBeach model version and mode used in the numerical modelling.

Simulation	Model version	Mode
sim1	Kingsday	Surfbeat
sim2	Kingsday	Non-Hydrostatic
sim3	XBeachX	Surfbeat
sim4	XBeachX	Non-Hydrostatic

The advanced default model parameter values recommended by the developers were considered, and the following parameters and conditions were applied in the model setup. In all simulations, a 2D absorbing-generating boundary condition was imposed at the offshore boundary. A morphodynamic acceleration factor (morfac) of 6 was considered to obtain the 48 hours morphological evolution, reducing the computational time without compromising the resolution of the hydro-morphodynamic processes and their interactions. In the SB simulations, a second-order upwind numerical scheme was used. In the NH simulations, a Warming and Beam scheme was used. In sim3, the new *single_dir* option was considered. The wave direction is solved at regular intervals using the stationary solver, and then the wave energy is propagated along the mean wave direction (Roelvink *et al.*, 2018), considering a bin size of 10º. In sim4, the new reduced two-layer model was used (*nonhq3d*). This improves the accuracy in modelling the frequency dispersion of the NH model due to the additional layer in comparison to the depth-averaged formulation.

3. RESULTS AND DISCUSSION

The bottom configuration of the model after 48 hours of bottom update in response to the wave induced sediment fluxes and the contour maps of the morphological differences for the same period, are presented in Figure 2 for sim1, sim2 and sim3 and in Figure 3 for sim4. In the contour maps, green and red represent accretion and erosion, respectively.

3.1 Simulation 1: Kingsday Surfbeat

In sim1, after 48 hours of morphological evolution, the model predicted: i) a retreat of the coastline (the 2 m ZH bathymetric line) and generalised erosion of the beach face, more intense on the lee side of the groyne (max. Δz=-0.6 m); ii) a submerged sandbar updrift of the groyne as a result of the beach face sediments deposition (max. Δz=1 m), extending up to half of the groyne length; iii) a smaller accretion area at the upper beach face on the lee side up to ¼ of the structure length (max. Δz=0.8 m); iv) erosion around the groyne (max. Δz=-0.4 m), on a wider area on the updrift side beyond its head and on the centre of the lee side domain up to the groyne length; and v) an erosive hotspot (max. Δz=-1 m) on the updrift side of the groyne head.

3.2 Simulation 2: Kingsday Non-Hydrostatic

In sim2, the morphological evolution shows general patterns similar to those of sim1 but with the following characteristics: i) a smaller (-5 m) coastline retreat updrift of the groyne and a less intense generalised erosion of the beach face downdrift; ii) a narrower and shorter (max. Δz=0.8 m) sandbar updrift of the groyne; iii) smaller and wider erosion areas respectively updrift and downdrift of the groyne, although maintaining the same intensity; and iv) a small accretion area (max. Δz=0.6) on the downdrift side of the groyne head that in sim1 had almost no expression.

3.3 Simulation 3: XBeachX Surfbeat

In sim3, the morphological changes predicted around the structure are more intense than in sim1 and sim2. Sim3 predicted: i) a more intense generalised erosion of the beach face than in sim1 and sim2, and consequently, a coastline retreat approximately 30 m larger; ii) a more intense beach face erosion downdrift of the structure (max. Δz=-1.6 m) than on the updrift side (max. Δz=-1 m); iii) a wider sandbar (max. Δz=1 m) resulting from deposition of the beach face sediments, reaching the same cross-shore extension as the head of the structure; iv) a wider accretion area on the landwards lee side of the groyne (max. Δz=1 m), further seawards in comparison to the previous simulations; v) a noticeably larger and more intense accretion on the downdrift side of the groyne head (max. Δz=1 m), resulting in the formation of a downdrift directed oblique submerged sandbar; vi) a wider intense erosion area on the updrift side of the groyne, focused near the groyne head (max. Δz=-1 m); and vii) a generalised erosion across the domain downdrift side.

3.4 Simulation 4: XBeachX Non-Hydrostatic

In sim4, the morphological changes predicted show higher bottom gradients than the other three simulations. The model predicted: i) a generalised erosion of the beach face (max. Δz=-0.4 m) followed by a disrupted slightly pronounced alongshore sandbar (max. Δz=0.6 m); ii) a coastline retreat similar to the predicted in sim1; iii) an erosive tendency in the overall model domain after 48h; iv) a greatly enhancement (max. Δz=-4.5 m) of the erosion hotspot previously identified near the groyne head, here widened southwards; and v) the formation of an oblique sandbar with similar alignment to the incident wave direction on the downdrift side of the groyne head. This feature, inexistent in sim1 and sim2, is noticeably more robust (max. Δz=1.2 m) near the groyne head and longer than in sim3. It reveals a shoreward growth that almost reaches the beach face.

3.5 Discussion

The results presented in the above-mentioned version-mode combinations of XBeach reveal the following morphological evolution features: a) retreat of the coastline; b) erosion of the beach face; c) formation of a submerged longshore sandbar in the upper profile at the updrift side of the groyne; d) accretion at the base of the of the groyne at the downdrift side; e) erosion hotspot near the groyne head; and f) formation of a longshore oblique sandbar downdrift of the groyne head. Features a), b) and c) are observed in the results of both versions and modes, and are characteristic of the short-term beach response when subjected to an erosive wave, when erosion of the upper beach leads to the subsequent seawards sediment transport and deposition. Features d), e) and f) can also be found in the presence of a groyne but reduced knowledge is available on the hydro-morphological conditions under which they are formed – Hs, Tp, Dir, d_{50}, bottom slope. The main reason is the difficulty to keep track of the location of these features, for being in a zone of permanent wave breaking.

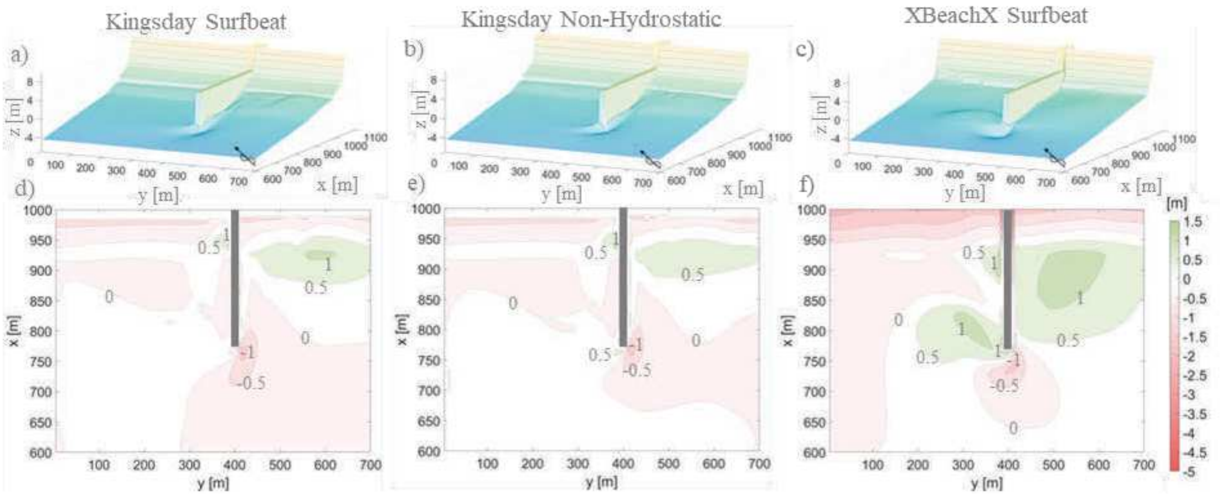

Fig. 2. Bottom configuration of the morphodynamic model after 48 hours of morphological evolution for simulations 1 (a), 2 (b) and 3 (c). Map of morphological differences (48 hours) for simulations 1 (d), 2 (e) and 3 (f): accretion in green, erosion in red. The arrows in (a), (b) and (c) indicate the incident wave direction.

The erosion of the beach face (b) is similar in both Kingsday modes, as the sandbar in the upper profile (c) and the overall erosion pattern. The sandbar accretion is less intense in the NH mode, probably due to the reflection and diffraction processes accounted for in this mode that can cause the seawards deflection of the sand that was extracted from the beach face and deposited in the alongshore bar, as can be seen in Figure 3b. These features are much more intense in the XBeachX SB mode, as the coastline retreat (a). This can be due to the *single_dir* option introduced in XBeachX: the wave group does not spread as much and diffusion is slower, leading to better defined (involving greater volumes) erosion/accretion patterns. In the XBeachX NH mode, features a), b) and c) are more irregular than the ones observed in the other simulation results, and d) is not predicted.

The accretion near the groyne base (d) and the erosion hotspot near the head (e) are similarly predicted in both Kingsday modes and are more intense in the XBeachX SB mode, for the same reasons mentioned for the previous features. In XBeachX NH the erosion hotspot e) is considerably wider and the maximum erosion predicted is four times higher than in the other simulations, most likely due to wave reflection and diffraction associated with the two-layer hydrodynamic model. These processes play a relevant part in supplying the submerged sandbar (f), already predicted in the SB mode of the same version, with the eroded sediments. The account of these processes results in the formation of a longer, more pronounced oblique sandbar in the groyne head with similar alignment to the incident wave direction. This feature is inexistent in the Kingsday version.

The results indicate that the NH mode can be used for morphological evolution modelling in the same way as the SB mode, despite the limited number of parameters available for a real case study calibration in this mode. It allows a detailed analysis of the hydrodynamic conditions and considers relevant processes when modelling a scenario in the presence of a hard structure (diffraction and reflection), that are not available in the SB mode. The most recent version, XBeachX, enables the model to predict new physical features regarding the previous Kingsday version, such as the groyne head oblique sandbar.

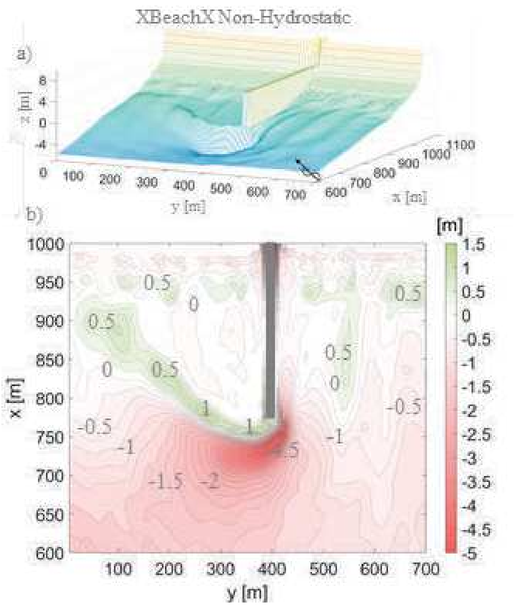

Fig. 3. Bottom configuration of the morphodynamic model (a) and map of differences (b) after 48 hours of morphological evolution for simulation 4. Accretion in green, erosion in red. The arrow in (a) indicates the incident wave direction.

CONCLUSIONS

This study investigates the morphological evolution tendencies predicted using the Surfbeat (SB) and Non-hydrostatic (NH) modes of the two latest XBeach-2DH versions, for a setup of reference forced by a 48 hours simple stationary erosive wave scenario, in the presence of a groyne. The results obtained for an equivalent model setup show that: i) the NH mode predicts similar morphological changes as the morphology-oriented SB mode; ii) the latest version (XBeachX, 2018) modifications and updates to the existing formulations, numerical schemes and default values, enable the model to predict physical features not identifiable in the previous version (Kingsday, 2015), such as the formation of a submerged sandbar downdrift of the groyne head; and iii) the NH XBeachX mode estimates a significantly higher erosion than the other version-mode combinations of the model. The selection of the appropriate XBeach version-mode combination to model a specific scenario must be done according to the topo-bathymetry and structure characteristics, and the hydro-morphological parameters available for the model calibration.

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