MODELLING OVERWASH VULNERABILITY ALONG MIXED SAND-GRAVEL COASTS WITH XBEACH-G: CASE STUDY OF PLAYA GRANADA, SOUTHERN SPAIN

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This work aims to calibrate the XBeach-G model on a mixed sand-gravel deltaic coast (Playa Granada, southern Spain) and apply it to address the overwash vulnerability. Field surveys, consisting of topographical measurements and sediment sampling in two selected areas, were performed before and after two extreme southwesterly storms. A calibrated wave propagation model (Delft3D-WAVE) was used to obtain the inshore conditions required to drive the XBeach-G model. The XBeach-G results for the coarse gravel fraction, a sediment friction factor of 0.03 and a Nielsen's boundary layer phase lag of 20º were found to provide the best fits to the observed morphological changes of the beach profile. This indicates that the morphodynamic response of the beach is dominated by the coarse gravel fraction, which is in agreement with previous experimental and numerical works carried out in the study site. The obtained brier skill scores and root-mean-square errors were higher than 0.89 and lower than 0.18 m, respectively, highlighting that the XBeach-G model is capable of reproducing the profile response under southwesterly storm conditions. The model was used to compute the required water level to generate overwash as a function of the wave height and direction, and results show how the application of XBeach-G can be used to address issues of storm-induced coastal vulnerability on gravel-dominated coasts.

Keywords: storm response; beach profile; XBeach-G; run-up; overwash

INTRODUCTION

Mixed sand-gravel (MSG) beaches are common in previously para-glaciated coastal regions and coasts with steep hinterlands across the world, such as the UK (Poate et al., 2016), Denmark (Clemmensen et al., 2016), Canada (Dashtgard et al., 2006), Mediterranean (Bramato et al., 2012) and New Zealand (Soons et al., 1997). They are also found when artificial nourishment projects use gravel to protect eroded sandy beaches (López de San Román-Blanco, 2004).

Although they have received increasing attention in recent years, the research advances on gravel and MSG coasts are limited compared to those on sandy beaches (Mason et al., 1997; Jennings and Shulmeister, 2002; Pontee et al., 2004; Buscombe and Masselink, 2006; López de San Román-Blanco et al., 2006; Horn and Walton, 2007). This discrepancy is particular relevant for numerical approaches (Orford and Anthony, 2011; Masselink et al., 2014), and contrast with the increasing coastal managers' demand for reliable models to handle global erosion problems (Syvitski et al., 2005; Anthony et al., 2014) and the expected sea-level rise in the coming years (Payo et al., 2016; Spencer et al., 2016).

In this context, several efforts have been made over last decade to develop a storm response model specific to gravel beaches (Pedrozo-Acuña, 2005; Pedrozo-Acuna et al., 2006; Pedrozo-Acuña et al., 2007; Van Rijn and Sutherland, 2011; Jamal et al., 2011, 2014; Williams et al., 2012), resulting in the implementation of a process-based model (XBeach-G) for the prediction of storm hydro- and morphodynamics of the beach profile (McCall et al., 2012, 2013; McCall, 2015). The model has been extensively validated on cross-shore dominated gravel beaches (McCall et al., 2014, 2015); however, it has not been tested on MSG coasts. The main objectives of this work are the validation and application of XBeach-G to investigate overwash vulnerability on a MSG beach in southern Spain.

STUDY SITE

Playa Granada is a 3-km-long micro-tidal MSG beach located on the southern coast of the Iberian Peninsula that faces the Alborán Sea (Figure 1). The beach corresponds to the central stretch of coast of the Guadalfeo deltaic system (Bergillos et al., 2015a) and is bounded to the west by the Guadalfeo River mouth and to the east by Punta del Santo, a former location of the river mouth (Figure 1).

The major contribution of sediments to the beach is provided by the Guadalfeo River. Its basin has an area of 1252 km^2, includes the highest peaks on the Iberian Peninsula (approximately 3400 m.a.s.l.), and is fed by one of the most high hydrological energy systems along the Spanish Mediterranean coast (Jabaloy-Sánchez et al., 2014). The topographic gradients lead to a wide range of sediment sizes in the Guadalfeo river sediment load (Millares et al., 2014).

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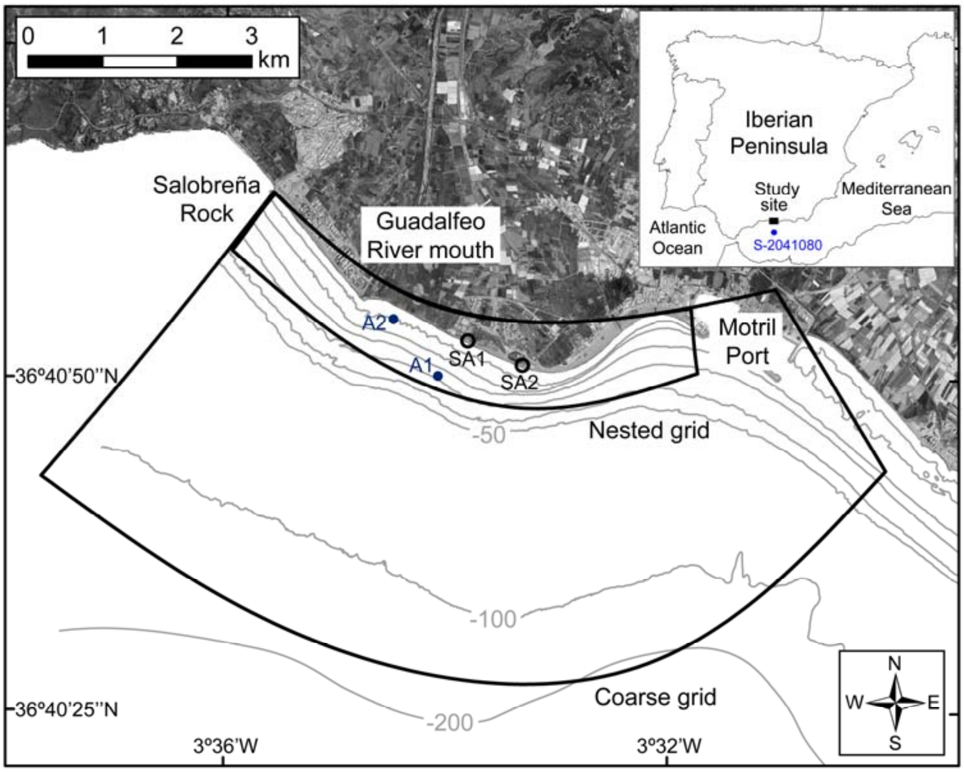

Figure 1. Location of the study site (Playa Granada, southern Spain), the two surveyed areas (SA1 and SA2) and the SIMAR point 2041080; bathymetric contours (in meters); grids used in the wave propagation model and positioning of the ADCPs (A1 and A2).

Consequently, the particle size distribution on the coast presents varying proportions of sand and gravel (Bergillos et al., 2015b), with three predominant fractions: sand (0.35 mm), fine gravel (5 mm) and coarse gravel (20 mm). The studied stretch of beach has presented a higher coastline retreat in recent years than both western and eastern stretches (Losada et al., 2011; Felix et al., 2012), which are known as Salobreña and Poniente Beach, respectively.

Climatic patterns at the study site exhibit a significant contrast between summer and winter. The wave climate is bimodal with prevailing west-southwest and east-southeast directions. The region is subjected to the passage of extra-tropical Atlantic cyclones and Mediterranean storms, with average wind speeds of 18-22 m/s (Ortega-Sánchez et al., 2003), which generate wind waves under fetch-limited conditions (approximately 200 to 300 km). The 50%, 90%, 99% and 99.9% exceedance significant wave heights in deep water (H_0) are 0.5 m, 1.2 m, 2.1 m and 3.1 m, respectively. The astronomical tidal range is ~0.6 m, whereas typical storm surge levels can exceed 0.5 m (Bergillos et al., 2016c).

METHODOLOGY

Model setup

The 1D process-based model XBeach-G is an extension of the XBeach model that incorporates: (1) a non-hydrostatic pressure correction term that allows solving waves explicitly in model; (2) a groundwater model that allows infiltration and exfiltration; and (3) the computation of bed load transport, including the effects of groundwater ventilation and flow acceleration forces, for estimating bed level changes (McCall et al., 2014, Masselink et al, 2014, McCall et al., 2015, McCall, 2015).

The model was tested in two study areas within the western section (SA1 and SA2, Figure 1) of the beach through topographical and sedimentological measurements of the upper profile (beach profile above the mean low water spring level) carried out before and after two extreme southwesterly storms (H_0>$H_{99\%}$) in December 2013 and March 2014 (Figure 2), detailed in Bergillos et al. (2016c). The infrastructures associated with the buildings located landward of the surveyed areas were included in the cross-shore profile as non-erodible objects.

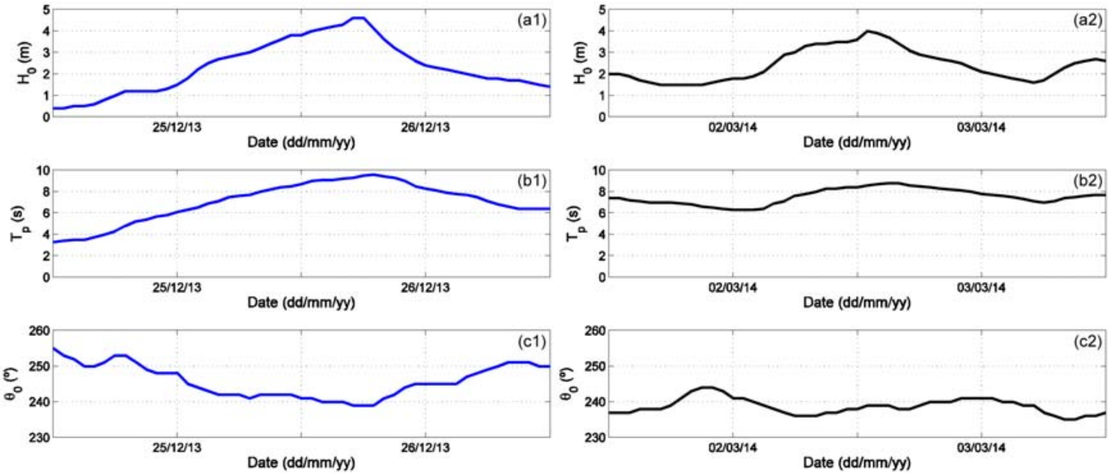

Figure 2. Evolution of the deep-water significant wave height (a), spectral peak period (b) and deep-water wave direction (c) during the storms of December 2013 (1) and March 2014 (2).

The three prevailing grain sizes (0.35 mm, 5 mm and 20 mm), five values of the sediment friction factor (0.01, 0.02, 0.03, 0.04 and 0.05) and six values of the Nielsen's boundary layer phase lag (0º, 10º, 20º, 30º, 40º and 50º; cf. Masselink et at., 2014) were tested during the calibration process of the model. The goodness of fit for each approach was evaluated through the root-mean-square error (RMSE, in m) and the brier skill score (BSS). All statistics were computed using data interpolated to a regularly-spaced grid and including only points where the measured or modelled bed level changes were greater than the maximum between the instrument error and $3D_{50}$ (cf. McCall et al., 2015).

The input wave boundary conditions were obtained from the Delft3D-WAVE model at a depth of 10 m. This water depth offshore boundary fulfils all requirements detailed in the manual of the XBeach-G model (Deltares, 2014), and is deeper than the closure depth in the study site (Bergillos et al., 2016b; Bergillos et al., 2017). The wave propagation model domain consisted of two different grids, shown in Figure 1. The first is a coarse curvilinear 82x82-cell grid covering the entire deltaic region, with cell sizes that decrease with decreasing depth from 88x60 to 48x35 m. The second is a nested grid covering the beach with 144 and 82 cells in the alongshore and cross-shore directions, respectively, and cell sizes of about 25x14 m. For the spectral resolution of the frequency space, 37 logarithmically-distributed frequencies ranging from 0.03 to 1 Hz were used; for the directional space, 72 directions covering 360° in increments of 5° were defined.

The Delft3D-WAVE model was calibrated through comparison with field data collected from 20 December 2014 to 30 January 2015 by means of two ADCPs (A1 and A2, Figure 1). The following physical processes were considered: wind effects, refraction, white-capping, depth-induced breaking ($\alpha = 1$, $\gamma = 0.73$), nonlinear triad interactions ($\alpha = 0.1$, $\beta = 2.2$), bottom friction (Type *Collins*, coefficient=0.02) and diffraction (smoothing coefficient=0.6, smoothing steps=600). The measured significant wave heights were compared with the equivalent wave heights propagated with the model for the same locations and coefficients of determination higher than 0.86 were obtained (Figure 3).

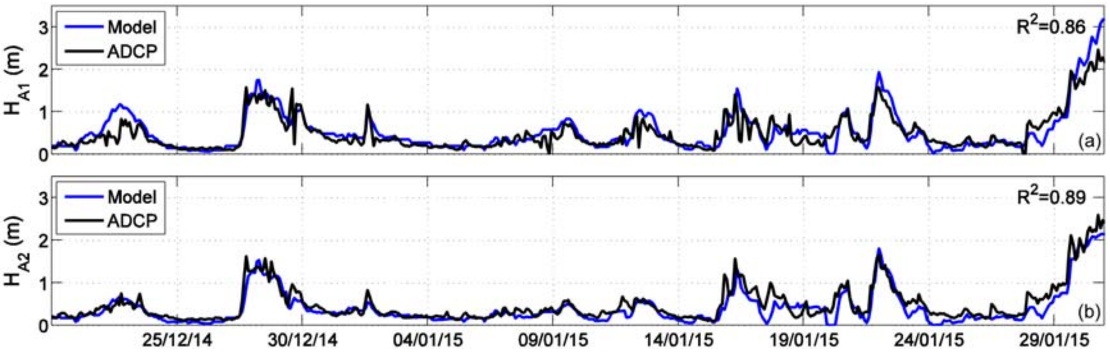

Figure 3. Comparisons between measured and modelled wave height time series for locations A1 (a) and A2 (b) according to Figure 1. (Source: Bergillos et al. (2016a). Reproduced with permission of Elsevier).

Modelling of overwash vulnerabilities

Based on field observations at the study site, Bergillos et al. (2016c) found that beach erosion/accretion depends not only on the wave height but on the sum of the three components that contribute to the total run-up (astronomical tide, storm surge and wave run-up). Thus, values of the total run-up higher than the height of the berm (negative free-board) generate beach erosion because of the overwash process (Matias et al., 2012, 2013), whereas those lower than the height of the berm (positive free-board) increase the unit volume of the beach, i.e., they generate beach accretion.

For this reason, after the calibration of the model, XBeach-G was used to compute the combination of water level (η) and deep-water significant wave height required to initiate overwash for two prevailing wave directions (107º and 238º) and a peak wave period of 9.3 s, according to the SIMAR 2041080 data (Figures 1 and 4). It was calculated for 69 shore-normal beach profiles equally distributed (1 every 100 m) along the entire deltaic coastline between Salobreña Rock and Motril Port.

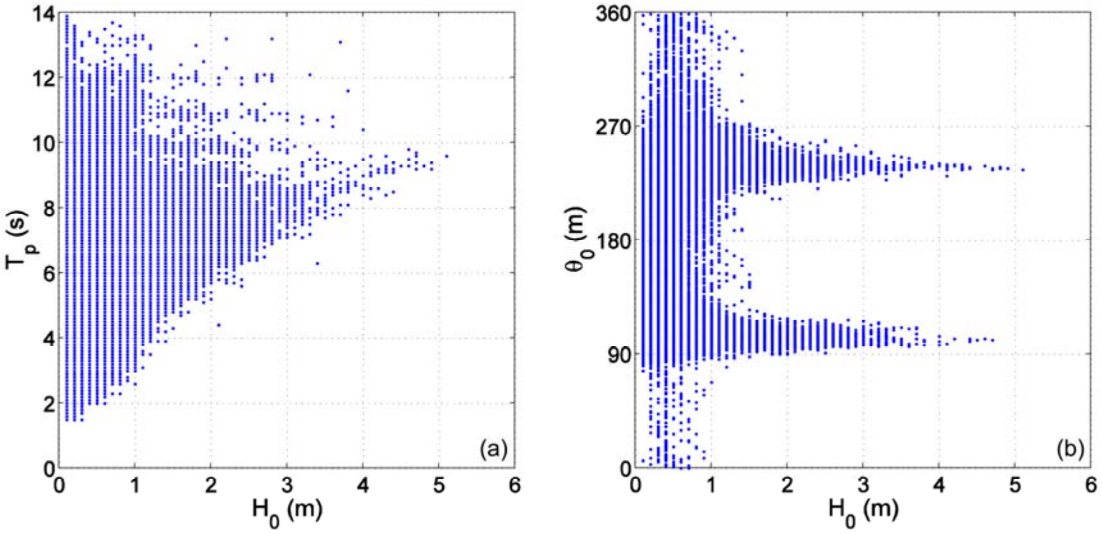

Figure 4. (a) Distribution significant wave height in deep water – spectral peak period and (b) distribution significant wave height in deep water – wave direction in deep water, based on the SIMAR 2041080 data.

RESULTS AND DISCUSSION

Model calibration

The best fits to the measured profiles after both storms for both study areas were obtained by assuming that the MSG is made up of gravel (D_{50}=20 mm, Figure 5). This is consistent with observations on the study site detailed by Bergillos et al. (2016c), who found that the morphodynamic response of the beach is dominated by the coarse gravel fraction due to the selective removal of the finer material (Bergillos et al., 2016c) and the reflective shape of the profile is similar to those found on pure gravel beaches (Masselink et al., 2010; Poate et al., 2013). Bergillos et al. (2017) also demonstrated that the best fits to the measured shorelines are obtained for the coarse gravel fraction.

The optimum values of the sediment friction factor and Nielsen's boundary layer phase lag were 0.03 and 20º, respectively, which are slightly different to those found on pure gravel beaches (0.01 and 25º, respectively) by Masselink et al. (2014). The goodness-of-fit parameters obtained with these optimum values (BSS>0.89 and RMSE<0.18 m, Table 1) show that the XBeach-G model is capable of reproducing the morphodynamic response of this MSG beach under southwesterly storms.

Table 1. Root-mean-square error (RMSE) and brier skill score (BSS) of the modelled changes relative to the measurements of the upper profile.

	Storm 2013		Storm 2014	
	RMSE (m)	BSS	RMSE (m)	BSS
Surveyed area 1	0.145	0.946	0.168	0.931
Surveyed area 2	0.154	0.912	0.176	0.893

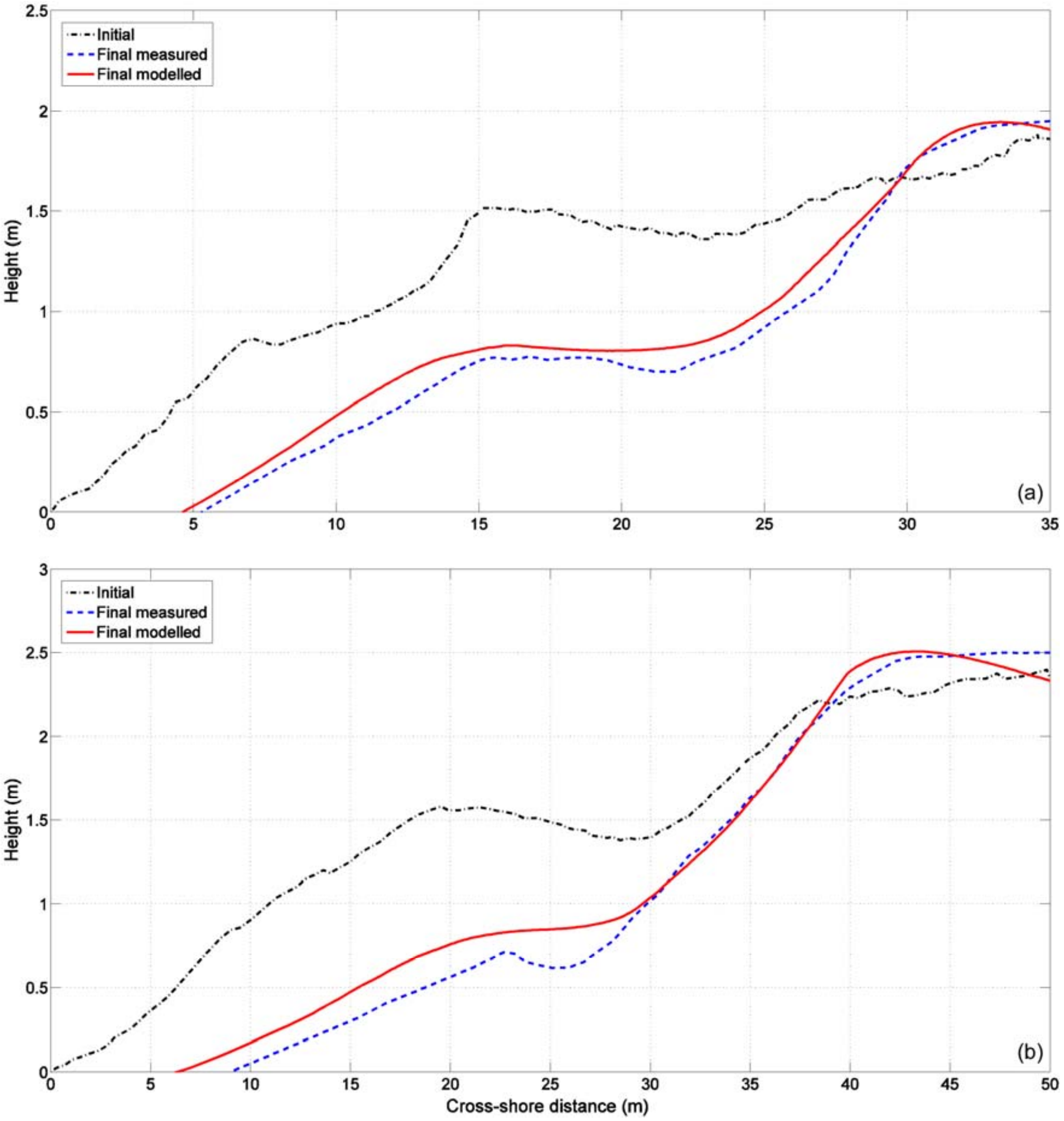

Figure 5. Initial, final measured and final modelled profiles in study areas 1 (a) and 2 (b) for the storm of December 2013. Height=0 indicates the mean low water spring level.

Coastal vulnerability to storm-induced overwash

Figure 6 depicts the alongshore distribution of the wave run-up (middle panels) and the required water level (lower panels) to generate overwash for five values of deep-water significant wave height (H_0=1–5 m) and the prevailing wave directions of 238º (left panels) and 107º (right panels). It is observed that the western (eastern) section of the beach is more sensitive to incoming westerly (easterly) waves. For a constant H_0, the beach is more vulnerable under incoming westerly waves, as they generate higher maximum values of wave run-up. Specifically, the section between the Salobreña Rock (alongshore distance=0) and the Guadalfeo River mouth is the most vulnerable, since the heights of the beach/barrier crest (hc) are relatively low at this location.

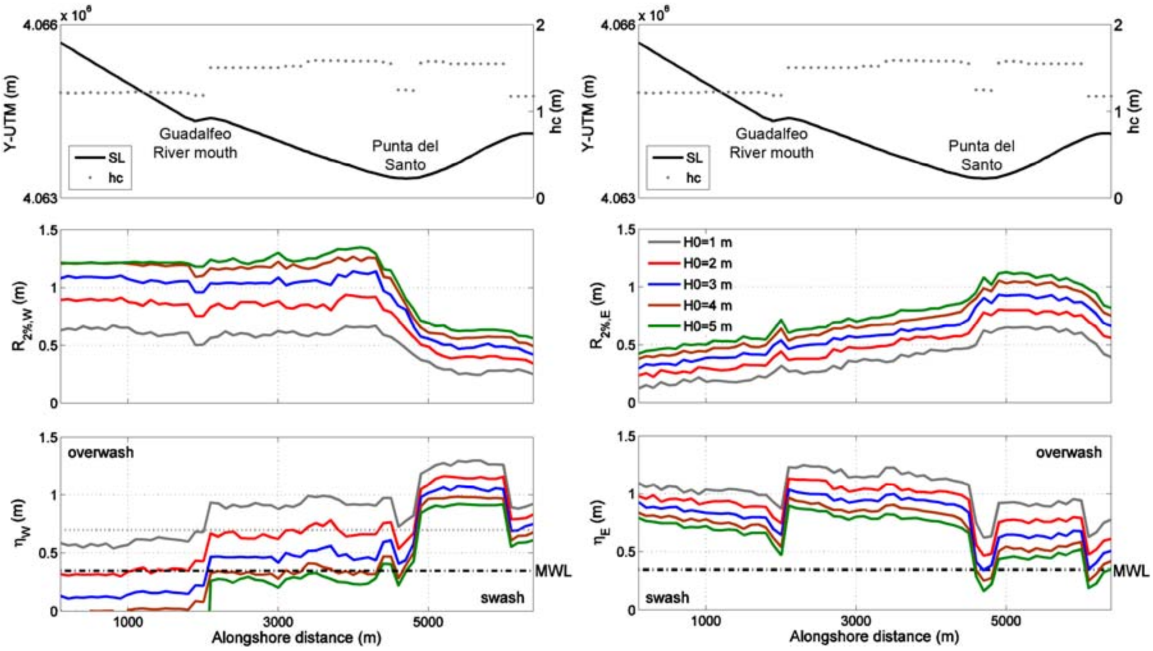

Figure 6. Alongshore variation of the height of the crest/berm (upper panels), wave run-up (middle panels) and required water level to generate overwash (lower panel) under westerly (left panels) and easterly (right panels) waves. The water level and height of the crest are referred to the mean low water spring level.

CONCLUSIONS

Although gravel and mixed sand-gravel coasts have received increasing attention during recent years, relatively few numerical models have been applied to and compared with field data for these coastal settings. This work models the morphological storm response and the overwash vulnerability of Playa Granada (southern Spain) by means of the application of the XBeach-G model.

The comparison of measured and modelled beach profiles reveals that the best fits are obtained for a sediment friction factor of 0.03, a Nielsen's boundary layer phase of 20º and a grain size of 20 mm. This is in agreement with previous experimental (Bergillos et al., 2016c) and numerical (Bergillos et al., 2017) works carried out in the study site. The goodness-of-fit parameters obtained (BSS>0.89 and RMSE<0.18 m) highlight that the XBeach-G model is capable of reproducing the response of the surveyed area (section Guadalfeo River mouth - *Punta del Santo*) under southwesterly storms. XBeach-G was used to compute the required water level to generate overwash as a function of the wave height and wave direction. Results showed how the application of an appropriately validated XBeach-G model can be used to address issues of coastal vulnerability to storm-induced overwash on MSG beaches.

However, the model has not been tested under southeasterly waves, which generate higher longshore sediment transport gradients at the study location. Therefore, future research should focus on the coupling of XBeach-G and longshore sediment transport equations to model the morphological response along the western (eastern) section under southeasterly (southwesterly) storm conditions. This approach could provide more confident predictions of the storm response on coasts dominated by both cross-shore and longshore sediment transport, such as beaches with different coastline orientations and/or forced by varying wave directions.

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