Coastal Engineering 129 (2017) 93–104

Contents lists available at ScienceDirect

Coastal Engineering

journal homepage: www.elsevier.com/locate/coastaleng

Coupling cross-shore and longshore sediment transport to model storm response along a mixed sand-gravel coast under varying wave directions

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A R T I C L E I N F O

Keywords:
Storm response
Beach profile
Wave propagation
XBeach-G
Longshore sediment transport

A B S T R A C T

This paper investigates the profile response of a mixed sand-gravel deltaic beach (Playa Granada, southern Spain) forced by storm waves from varying directions. Beach morphology was monitored over a 36-day period with variable wave conditions, and profile response was compared to model predictions using the XBeach-G model and a longshore sediment transport (LST) formulation. XBeach-G was applied over 2-day periods of low energy, south-westerly (SW) storm and south-easterly (SE) storm conditions, and was coupled to LST using a parametric approach which distributes the LST across the swash, surf and nearshore zones. A calibrated wave propagation model (Delft3D) was used to obtain the inshore conditions required to drive the XBeach-G model and the LST formulation. The storm response is clearly influenced by the free-board (difference between the height of the berm and the total run-up) and is also strongly dependent on storm-wave direction, with the SW storm eroding the surveyed area, while the SE storm induced beach accretion. Model results indicate that XBeach-G on its own is capable of adequately reproducing the response of the beach under SW storm conditions ($BSS > 0.95$), but not under SE storms due to the higher LST gradients at the study location. The combination of XBeach-G and LST fits the measured profiles reasonably well under both SW ($BSS > 0.96$) and SE ($BSS > 0.88$) storms, inspiring confidence in the coupled model to predict the storm response under varying wave conditions. The combined XBeach-G/LST model was applied to the entire 6.8-km deltaic coastline to investigate the impact of extreme SW and SE storm events, and the model results reiterate the importance of cross-shore and longshore sediment transport in driving coastal storm response at this location. The approach proposed in this work can be extended to other worldwide coasts highly influenced by both cross-shore and longshore sediment transport, such as beaches with different coastline orientations and/or forced by varying wave directions.

1. Introduction

Gravel and mixed sand-gravel (MSG) beaches are common in previously para-glaciated coastal regions and coasts with steep hinterlands, and are widespread in the UK (Carter and Orford, 1984; Poate et al., 2016), Denmark (Clemmensen and Nielsen, 2010; Clemmensen et al., 2016), Canada (Engels and Roberts, 2005; Dashtgard et al., 2006), Mediterranean (Bramato et al., 2012; Bergillos et al., 2016c) and New Zealand (Shulmeister and Kirk, 1993; Soons et al., 1997). They are also found when nourishment projects use gravel to protect eroded sandy beaches (López de San Román-Blanco, 2004; Moses and Williams, 2008). Among these coastal settings, a distinction can be made between drift-aligned systems (e.g., Shaw et al. (1990); Carter and Orford (1991)), where alongshore sediment exchange plays the main role in driving shoreline dynamics, and swash-aligned areas (e.g., Orford and Carter (1995); Orford et al. (1995)), which are dominated by cross-shore sediment transport (Forbes et al., 1995; Orford et al., 2002).

Despite their societal importance, the research advances on gravel and MSG beaches 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 particularly evident for numerical approaches (Orford and Anthony, 2011; Masselink et al., 2014), and contrasts strongly with the increasing demand for reliable coastal change models to help mitigate and adapt to global erosion problems (Syvitski et al., 2005; Anthony et al., 2014) and future sea-level rise (Payo et al., 2016; Spencer et al., 2016). Several efforts have been made over the last decade to develop a morphodynamic storm response

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https://doi.org/10.1016/j.coastaleng.2017.09.009
Received 2 November 2016; Received in revised form 12 July 2017; Accepted 15 September 2017

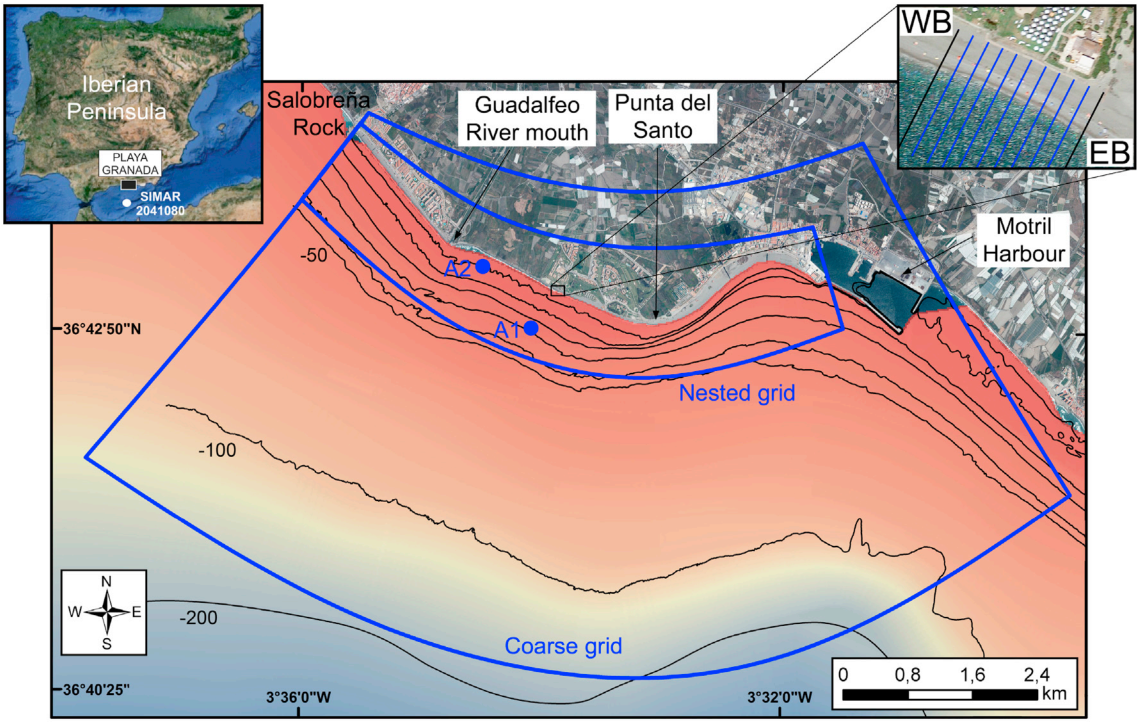

Figure 1. Upper left panel: Location of the study site (Playa Granada, southern Spain) and the SIMAR point 2041080. Central panel: bathymetric contours, grids used in the wave propagation model and positioning of the ADCPs (A1 and A2). Upper right panel: west (WB) and east (EB) boundaries of the surveyed area and measured beach profiles.

model specific to gravel beaches (Pedrozo-Acuña, 2005; Pedrozo-Acuña et al., 2006, 2007; Van Rijn and Sutherland, 2011; Jamal et al., 2011, 2014; Williams et al., 2012). In the present paper, we use the XBeach-G model (McCall et al., 2012, 2013; McCall, 2015), as it has been validated most extensively using both laboratory and field data (McCall et al., 2014, 2015; Almeida et al., 2017).

XBeach-G is a 1D process-based model specifically developed to model cross-shore storm response on gravel beaches. However, in drift-aligned systems, where longshore sediment transport (LST) plays a key role in controlling the coastal behaviour (Orford et al., 1991; López-Ruiz et al., 2014), a cross-shore profile model is clearly not sufficient to model storm response. Drift-aligned systems could be coastlines with a highly variable shoreline orientation and a uni-directional, but spatially-variable LST. Alternatively, they could be coastlines subjected to a bi-directional wave climate characterized by temporal variations in the frequency of the incoming wave directions and, as a consequence, in the net littoral drift (French and Burningham, 2015; Bergillos et al., 2016a). In these coastal areas, it is particularly important to consider not only the cross-shore sediment transport, but also the effects of LST (De Alegría-Arzaburu and Masselink, 2010; Masselink et al., 2016). Recent advances are available to estimate LST on sand, gravel and shingle beaches (Van Rijn, 2014); but the cross-shore distribution of LST, widely studied on sandy beaches (e.g., Berek and Dean (1982); Komar (1983); Kamphuis (1991); Bayram et al. (2001)) and relevant for modelling coastal response, has not been investigated in depth on gravel and MSG beaches (Van Wellen et al., 1998; Van Wellen et al., 2000).

The main objectives of this paper are to characterize and to model the storm response of an MSG beach (Playa Granada, southern Spain) under varying wave directions. Thirteen field surveys were performed and a numerical model (Delft3D) calibrated for the study site was used to relate the wave propagation patterns with the coastal dynamics. Delft3D results were also used to apply and test the XBeach-G model forced by low energy (LE) conditions, and south-westerly (SW) and south-easterly (SE) storms. In addition, XBeach-G was combined with the LST equation of Van Rijn (2014) by means of a parametric formulation to consider different cross-shore distributions of LST. Finally, the approach that best fitted the observed response was used to model extreme SE and SW storms along the entire deltaic coastline, highlighting the potential of the proposed coupled model to extend XBeach-G towards larger longshore scales.

2. Study site

Playa Granada is a 3-km long micro-tidal beach located on the southern coast of Spain that faces the Mediterranean Sea (Fig. 1). The beach corresponds to the central stretch of the Guadalfeo deltaic plain (Bergillos et al., 2015c) and is bounded to the west by the Guadalfeo River mouth and to the east by *Punta del Santo*, the former location of the river mouth (Fig. 1). The deltaic coast is bounded to the west by Salobreña Rock and to the east by Motril Harbour. This harbour is an artificial barrier that prevents LST (Félix et al., 2012).

The Andalusian littoral of the Mediterranean Sea is characterized by the presence of high mountainous relief angles and short fluvial streams. The Guadalfeo River contributes most sediment to the beach (Bergillos et al., 2016d). Its basin covers an area of 1252 km^2, including the highest peaks on the Iberian Peninsula ($\sim$ 3400 m.a.s.l.), and the river is associated with one of the most high-energy drainage systems along the Spanish Mediterranean coast. These steep topographic gradients lead to a wide range of sediment sizes in the Guadalfeo river sediment load (Millares et al., 2014).

Consequently, the particle size distribution on the coast is particularly complex, with varying proportions of sand and gravel. Although three sediment fractions are predominant in the studied coastal area –sand (0.35 mm), fine gravel (5 mm) and coarse gravel (20 mm)– (Bergillos et al., 2015a), 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 gravel beaches (Masselink et al., 2010; Poate et al., 2013). Previous numerical works also demonstrated that the best fits to the measured profiles (Bergillos et al., 2016b) and shorelines (Bergillos et al., 2017) are obtained by assuming that the beach is made up of coarse gravel.