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The role of wave energy converter farms on coastal protection in eroding deltas, Guadalfeo, southern Spain

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ABSTRACT

Many worldwide coasts are under erosion with climate projections indicating that damages will rise in future decades. Specifically, deltaic coasts are highly vulnerable systems due to their low-lying characteristics. This paper investigates the role of wave energy converter (WEC) farms on the protection of an eroding gravel-dominated deltaic coast (Guadalfeo, southern Spain). Eight scenarios with different alongshore locations of the wave farm were defined and results were compared with the present (no farm) configuration of the coast. Assuming that storm conditions drive the main destruction to the coast, we analysed the impact of the most energetic storm conditions and quantified the effects of the location of the farm. Significant wave heights in the lee of the farm were calculated by means of a calibrated wave propagation model (Delft3D-Wave); whereas wave run-up and morphological changes in eight beach profiles were quantified by means of a calibrated morphodynamic model (XBeach-G). The farm induces average reductions in significant wave heights at 10 m water depth and wave run-up on the coast down to 18.3% and 10.6%, respectively, in the stretch of beach most affected by erosion problems (Playa Granada). Furthermore, the erosion of the beach reduces by 44.5% in Playa Granada and 23.3% in the entire deltaic coast. Combining these results with previous works at the study site allowed selecting the best alternative of wave farm location based not only on coastal protection but also on energetic performance criteria. This work, whose methodology is feasibly extensible to other coasts worldwide, provides insights into the role of the alongshore location of WEC farms on wave propagation, run-up and morphological storm response of deltaic coasts.

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1. Introduction

Over the last decades, human activities, such as channelization, channel deviation or river regulation, have altered the natural dynamics of deltaic coasts and generated erosion problems across the world (Syvitski and Saito, 2007; Syvitski et al., 2009; Anthony et al., 2014; De Leo et al., 2016). These areas are particularly vulnerable not only to human-driven changes but also to the effects of global warming (Jeftic et al., 1996; Nicholls and Hoozemans, 1996). In this context, it is essential to investigate strategies for mitigating and/or adapting to global erosion problems (Syvitski et al., 2005; Anthony, 2015) and future consequences of sea-level rise (Payo et al., 2016; Spencer et al., 2016).

On the other hand, the exploitation of renewable energy resources as sustainable alternatives to fossil fuels is another important challenge that society should face in the next decades (Nie et al., 2016; González et al., 2017); accordingly, it has received increasing research interest during last decade (Huenteler et al., 2016; Kung et al., 2017). Among the different ocean energy sources, wave energy boasts one of the highest densities of the renewable energy technologies (Clément et al., 2002), its environmental impacts are relatively low (Lin and Yu, 2012) and the availability of places to allocate wave energy facilities is quite extensive (López-Ruiz et al., 2017). This source is also called to play a major role to achieve the European Union objectives for 2020 in regards to the renewable energy sector (Commission et al., 2007).

Recent works on wave energy converters (WECs) have pointed out that optimal performances can be attained for waves with relatively short peak periods (e.g., López et al. (2015) or Jalón et al.

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(2016)). That is a key finding for the Mediterranean coasts, where wave climate is predominantly moderate (Ortega-Sánchez et al., 2017). The performance and management of WECs working at the nearshore have also received increasing attention in the last few years (e.g., Veigas et al. (2014), López-Ruiz et al. (2016) or Medina-López et al. (2017)).

When WEC farms are located near the shore, they have been found to act as coastal defence elements due to both the wave energy absorbed by the array and the dissipation induced by the obstacles, with many works showing the significant reduction in the wave heights in the leeward side of the farms (Beels et al., 2010; Palha et al., 2010; Ruol et al., 2011; Carballo and Iglesias, 2013; Monk et al., 2013; Rusu and Soares, 2013; Zanuttigh and Angelelli, 2013; Iglesias and Carballo, 2014). The effects of wave farms on the morphological responses of both the coastline (Millar et al., 2007; Mendoza et al., 2014) and beach profile (Abanades et al., 2014a, b; 2015) have also been quantified on sandy beaches. Thus, devices for the exploitation of marine energy sources bring an opportunity to enhance the sustainable management of the coastal zone.

However, to our best knowledge: (1) the influence of WEC farms on the morphological storm response has not been assessed in deltaic environments; (2) the farm-induced variations in wave run-up and their implications on coastal flooding have not been studied in depth; and (3) the role of alongshore location of WEC farms in deltas protection has not been addressed.

The main objectives of this paper are to quantify and to analyse the influence of the alongshore location of wave farms on the hydro- and morphodynamics of a gravel-dominated deltaic coast (Guadalfeo, southern Spain) under storm conditions. To meet these goals, wave propagation patterns, wave run-up and morphological changes of the beach were assessed by means of the application of calibrated wave propagation and morphodynamic models to eight different scenarios of wave farm location. All results were compared to the current situation (no farm) and the best alternative was selected, based on energetic performance and coastal protection criteria. The latter was quantified as the reductions in nearshore wave height, wave run-up and beach erosion.

This paper is structured as follows. Sections 2 and 3 describe the study site and methods used to carry out this research, respectively. Section 4 details the results, namely, the influence of WEC farms on wave propagation, run-up and morphological changes of the beach as a function of the alongshore location. Finally, the conclusions of the work are summarized in Section 5.

2. Study site

The Guadalfeo deltaic coast is a 6.8-km-long micro-tidal beach located on the southern coast of Spain that faces the Mediterranean Sea (Fig. 1). It is bounded to the west by Salobreña Rock and to the east by Motril Port (Félix et al., 2012). 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 (Millares et al., 2014).

The river was dammed 19 km upstream from the mouth in 2004, regulating 85% of the basin run-off (Losada et al., 2011). As a consequence of river damming, the delta currently experiences coastline retreat, severe erosion problems (Bergillos et al., 2015c) and frequent coastal flooding (Fig. 2). The central stretch of beach (Playa Granada) has been particularly affected and has been subjected to higher levels of coastline retreat in recent years than both western and eastern stretches, known as Salobreña and Poniente Beach, respectively (Fig. 1). Consequently, artificial nourishment projects have been frequently conducted since the entry into operation of the dam (Bergillos et al., 2015b). However, the success of these interventions has been very limited since they lasted on average less than three months (Bergillos and Ortega-Sánchez, 2017).

The particle size distribution on the studied coastal area presents varying proportions of sand and gravel (Bergillos et al., 2015a), with three predominant fractions: sand ($\sim$ 0.35 mm), fine gravel ($\sim$ 5 mm) and coarse gravel ($\sim$ 20 mm). However, 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., 2017b) are obtained by assuming that the beach is made up of coarse gravel.

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 200–300 km). The storm wave climate is bimodal with prevailing west-southwest (extra-tropical cyclones) and east-southeast (Mediterranean storms) wave directions (Bergillos et al., 2016a). The 90%, 99% and 99.9% not exceedance significant wave heights in deep water are 1.2 m, 2.1 m and 3.1 m, respectively. The astronomical tidal range is $\sim$ 0.6 m, whereas typical storm surge levels can exceed 0.5 m (Bergillos et al., 2016c).

3. Methodology

To evaluate the efficiency of a wave farm as a coastal defence, the impacts of extreme south-westerly and south-easterly storms ($H_{99.9\%}$) were simulated using the Delft3D-Wave model and an extension of the XBeach-G model along the entire deltaic coast for eight different scenarios (Section 3.1). Each scenario corresponds to a different alongshore location of the wave farm (Fig. 3). These models were used because they are able to reproduce wave propagation patterns and storm-driven morphological changes, and they have been calibrated for the study site (Sections 3.2 and 3.3).

The modelled wave variables were $H_0 = 3.1$ m, $T_p = 8.4$ s (the most frequent period under storm conditions), $\theta_{0,SW} = 238^\circ$ and $\theta_{0,SE} = 107^\circ$ (the most frequent directions under south-westerly and south-easterly storms, respectively). These constant sea states, summarized in Table 1, were simulated considering a storm surge of 0.5 m for a duration of 6 h around high tide (tidal peak of 0.3 m), according to Bergillos et al. (2017a). These wave conditions were tested because storms are the main responsible of the erosion problems and coastal flooding in the study site.

3.1. Wave farm locations and geometry: scenarios

López-Ruiz et al. (2016) quantified the wave energy resource in 24 locations along the Guadalfeo deltaic coast during a 25-year period (typical lifetime of the WECs according to Margheritini et al. (2009) and Guanche et al. (2014), among others). The highest mean and extreme values of wave power were obtained at 30 m water depth, being the reason to define the eight wave farm scenarios (Fig. 3) with locations centred at this depth (A30 to H30 in López-Ruiz et al. (2016)). This range of water depths for the wave farm location is also in agreement with previous works (e.g., Mendoza et al. (2014), Abanades et al. (2014b) or López-Ruiz et al. (2017)).

Thus, we can compare and select the best scenario considering not only the availability of wave power, but also the hydrodynamic

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