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Wave farm impact on beach modal state

J. Abanades *, D. Greaves, G. Iglesias

Plymouth University, School of Marine Science and Engineering, Marine Building, Drake Circus, Plymouth PL4 8AA, UK

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ABSTRACT

The extraction of wave energy by the Wave Energy Converters (WECs) forming a wave farm results in a milder wave climate in its lee, which can have an impact on coastal processes. The objective of this work is to determine whether the beach morphology can be altered by the operation of the wave farm, and if so, to quantify this alteration. For this purpose, we examine how the farm affects the modal state of the beach with reference to a baseline (no farm) scenario. The modal state is defined based on an empirical classification that accounts for wave conditions, tidal regime and sediment size. As a beach typically goes through different modal states, we determine the percentages of time in an average year corresponding to each state in the baseline scenario, and how these percentages are altered by a wave farm as a function of its distance from the coast. This methodology is illustrated through a case study: Perranporth Beach (UK), an area of great potential for wave energy development. High-resolution numerical modelling is used, with two levels of grid refinement. We find that the wave farm has a relevant impact on the modal state of the system, which passes from wave-dominated to tide-dominated during significant periods of time. The sensitivity analysis, involving three cases with the farm at distances of 2 km, 4 km and 6 km from the beach, showed that the farm-to-coast distance plays a major role. Thus, the shift from a wave- to a tide-dominated beach is exacerbated in the case of the wave farm closest to the coastline, with the submarine bar vanishing over long periods of time. We conclude that the presence of the wave farm drastically alters the morphological response of the beach, and that this alteration is strongly dependent on the farm-to-coast distance.

1. Introduction

Wave energy is poised to become one of the major renewable energies in a number of coastal regions around the world (Bernhoff et al., 2006; Carballo et al., 2014; Cornett, 2008; Defne et al., 2009; Gonçalves et al., 2014; Iglesias and Carballo, 2010a; Iglesias et al., 2009c; Lenee-Bluhm et al., 2011; Liberti et al., 2013; Stopa et al., 2011; Veigas et al., 2014a; Veigas and Iglesias, 2013, 2014; Vicinanza et al., 2013). The influence of wave energy extraction by the Wave Energy Converters (WECs) forming a wave farm on the nearshore wave conditions was recently shown by different authors (Carballo and Iglesias, 2013; Iglesias and Carballo, 2014; Mendoza et al., 2014; Millar et al., 2007; Palha et al., 2010; Ruol et al., 2011; Smith et al., 2012; Veigas et al., 2014b,c; Vidal et al., 2007; Zanuttigh and Angelelli, 2013). Abanades et al. (2014b) proved that this extraction resulted in a medium-term reduction of the erosion exceeding 20% in some sections of the beach profile (2D). In further studies, Abanades et al. (2014a, 2015) considered the 3D response of the beach under storm conditions in order to establish the applicability of wave farms to coastal defence. Erosion was found to decrease by more than 50% in certain areas of the beach. In the wake of these studies, which evidence the impact of wave farms on beach morphology, the question arises as to whether a wave farm can modify the modal state of a beach, and, if so, in what manner.

The objective of the present study is to answer this fundamental question by means of a case study: Perranporth Beach (UK). To quantify the effects of the wave farm on the modal state of the beach, scenarios with and without the farm were compared and the percentage of time corresponding to the different modal states during the period from 1st of November 2007 to 31st of October 2008 was determined. In addition, the seasonal variability: "winter" (Nov–Apr) vs "summer" (May–Oct) was also examined. The modal states were established following the empirical classification presented by Masselink and Short (1993), based on Wright and Short (1984). The modal states vary as a function of the wave climate (breaking wave height and peak period), the beach sediment characteristics (sediment fall velocity) and the tidal regime (mean spring tidal range).

The effects of the wave farm on the coast are characterised using a wave propagation model, SWAN (Booij et al., 1996). The wave farm, which consists of eleven WaveCat WECs arranged in two rows, is implemented on a high-resolution grid so as to accurately resolve the wakes of the individual WECs, and hence that of the wave farm as a whole. Four scenarios are examined: three with the wave farm at different distances from a reference contour (10 m water depth): 2 km, 4 km and 6 km, following Abanades et al. (2015), plus the baseline scenario (without the wave farm). Thanks to the three distances considered it

* Corresponding author.
E-mail address: javier.abanadestercero@plymouth.ac.uk (J. Abanades).

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is possible to analyse the role of the farm-to-coast distance in the impact on the beach morphology. The WEC–wave field interaction is modelled by means of the wave transmission coefficient, obtained through laboratory tests as reported by Fernandez et al. (2012). The numerical model, successfully validated with wave buoy data, is used to calculate the wave conditions and on this ground establish the modal state of the beach.

The understanding and modelling of beaches are essential to coastal management (Budillon et al., 2006; Cowell et al., 1995; De Vriend et al., 1993; Hughes et al., 2014; Iglesias et al., 2009a,b; Ortega-Sánchez et al., 2014; Ortega Sanchez et al., 2003; Poate et al., 2014). In the case of Perranporth, the beach was described as dissipative (Butt et al., 2001; Masselink et al., 2005) and as a low-tide bar rip system (Scott et al., 2007, 2011), with Austin et al. (2010) indicating that it is at the transition between the low tide bar/rip and dissipative beach. In this context, the characterisation obtained in the present work contributes to understanding the behaviour of Perranporth by providing quantitative estimates of its morphodynamical variability throughout a year.

2. Material and methods

2.1. Conceptual beach model

The conceptual beach classifications are empirical models based on the relationships between the characteristics of different types of beaches (wave climate, sediment size and tidal regime) and field observations. Therefore, these models allow the evolution of beach dynamics as a function of the beach features to be predicted, and also, the quantification of the potential changes induced by a modification of these, such as the reduction of wave energy brought about by a wave farm.

The classification presented by Wright and Short (1984), also called the Australian beach model, is based on the field observations collected in Australia for microtidal beaches. This classification indicates the prevailing conditions in the surf zone: dissipative, intermediate or reflective, as a function of the dimensionless fall velocity parameter (Ω), also known as the Dean's number (Dean, 1973),

$$\Omega = \frac{H_b}{w_s T} \tag{1}$$

where H_b is the breaking wave height, T is the wave peak period corresponding to the breaking conditions and w_s is the sediment fall velocity, which is defined for the present paper according the Shore Protection Manual (US Army Corps Of Engineers, 1984),

$$B = \left(\frac{\gamma_s}{\gamma_w} - 1\right)\frac{gD_{50}^3}{\nu^2} \tag{2}$$

$$w_s = \begin{cases} \left(\dfrac{\gamma_s}{\gamma_w} - 1\right)\dfrac{gD_{50}^2}{18\nu}; & B < 39, \\ \left(\dfrac{\gamma_s}{\gamma_w} - 1\right)^{0.7}\dfrac{g^{0.7}D_{50}^{1.1}}{6\nu^{0.4}}; & 39 < B < 10^4 \\ \left[\left(\dfrac{\gamma_s}{\gamma_w} - 1\right)\dfrac{gD_{50}}{0.91}\right]^{0.5}; & B > 10^4 \end{cases} \tag{3}$$

where γ_s and γ_w are the densities of the sediment and water, respectively, g the gravitational acceleration, D_{50} the sediment grain size and ν the fluid kinematic viscosity.

This model represents the evolution of microtidal beaches well; however, it does not account for the influence of the tide on the swash, surf zone and shoaling wave processes (Davis and Hayes, 1984). This was corrected with the introduction of a new parameter: the relative tide range (RTR), which allows the characterisation of all wave-dominated beaches in all tidal ranges (Masselink and Short, 1993):

$$RTR = \frac{MSR}{H_b}, \tag{4}$$

where MSR is the mean spring tidal range.

Fig. 1 shows the relationships between the dimensionless fall velocity and the relative tide range parameters that are used to establish the modal beach state. As the RTR parameter increases the beach evolves from a classic reflective state through the formation of a low tide terrace at the toe of the beach face and low tide rips to a steep beach face fronted by a dissipative low tide terrace. In the case of an intermediate barred beach, the increase in the tidal range moves the bar down to the low tide level generating a low tide bar and rips. Finally, for barred dissipative beaches characterised by multiple subdued bars at different water depths, the increase of RTR results in the disappearance of these bars. The latter two groups shift to ultra-dissipative beaches with values of RTR between 7 and 15. For values of RTR greater than 15 the resulting beach is fully tide-dominated.

2.2. Case study: Perranporth Beach

The characterisation of the changes induced by a wave farm in the morphodynamical behaviour of a beach is conducted at Perranporth Beach (Fig. 2), a prospective site for wave energy exploitation for its prime location on the Atlantic façade of Europe, which has been highlighted for its wave energy resource (Guedes Soares et al., 2014; Iglesias and Carballo, 2009, 2010b, 2011; Pontes et al., 1996). An example of this potential is the Wave Hub project (Gonzalez-Santamaria et al., 2013; Reeve et al., 2011), a grid-connected offshore facility for sea tests of WECs, located in SW England. In addition to its wave energy potential, a further reason for choosing Perranporth is that this beach, facing directly the North Atlantic Ocean, has experienced increased erosion due to rising sea level and storminess — as corroborated by the extremely energetic storms of February 2014. Therefore, this would be a prime area for using a wave farm to control the storm-induced erosion (Abanades et al., 2014a,b, 2015).

Perranporth is an approx. 4 km beach composed by a medium sand size, $D_{50} = 0.27$–0.29 mm, and characterised by a low intertidal slope, $\tan\beta = 0.015$–0.025. In the present study, the offshore bathymetric data, from the UK data centre Digimap, and the beach profile data, obtained through field survey by the Coastal Channel Observatory, are implemented onto the wave propagation model. In the three beach profiles selected to determine the beach modal state the relevant features can be readily observed (Fig. 3): a submarine bar at a water depth between 5 and 10 m and a well-developed dune system that backs the landward end of the beach. The latter aspect does not play a role in the modal state, which only considers the intertidal area, but the bar system does — and is indicative of a dissipative or intermediate state. In the case of profile P3, two submarine bars are distinct — typical of a barred dissipative state.

As regards the wave conditions, wave buoy data are used in conjunction with hindcast data to force the wave propagation model. Hindcast data from WaveWatch III, a third-generation offshore wave model consisting of global and regional nested grids with a resolution of 100 km (Tolman, 2002), are used to prescribe the offshore boundary conditions. The validation is carried out with the wave buoy located off Perranporth Beach at a water depth of approx. 10 m. The average values of the significant wave height, peak period and direction from November 2007 to October 2008 were 1.60 m, 10.37 s and 282.59°, respectively. Dividing this period into "winter" (Nov–Apr) and "summer" (May–Oct) to analyse the seasonal variability of the beach, the values in "winter" of the significant wave height, peak period and direction were 1.98 m, 11.30 s and 285.23°, respectively, and in "summer" 1.32 m, 9.62 s and 279.95°.