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High frequency in-situ field measurements of morphological response on a fine gravel beach during energetic wave conditions☆

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ABSTRACT

This paper presents novel data collected over four weeks at Loe Bar, a fine gravel barrier ($D_{50} = 3.5$ mm), exposed to energetic wave conditions ($H_{s10\%} = 2.4$ m). Combined remote and in-situ measurements were used to identify 3D morphological response, profile change and runup behaviour during successive energetic periods ($H_s = 2.5$ m). Small intertidal beach volume losses occurred under high steepness waves ($H_0/L_0 > 0.01$), but, in general, the overall beach volume was remarkably stable. In fact, the greatest morphological response was evident not in cross-shore sediment exchanges, but due to the alongshore redistribution related to the three-dimensional beach cusp system. Specifically, during energetic wave conditions the cusp morphology underwent horn growth and embayment deepening, leading to increased cusp definition. An additional explanation for the stability of the cross-shore beach profile is related to the development of the beach step. During energetic conditions and long period waves, significant deposition (c. 1 m) occurred at the top of the beach step above the still water line. The enhanced step provided a focal point for wave breaking, considerably curtailing the swash motion and reducing the runup limit, thereby providing protection to the upper beach. This study provides much needed insight into complex morphological response and runup characteristics on gravel beaches, fundamental for improved model development, and leading towards better predictive tools.

1. Introduction

Gravel beaches and barriers, including mixed sand and gravel beaches, are typically found in mid-latitude regions often along paraglacial coasts (e.g., Canada, UK, Ireland), and they are also common along coastlines backed by mountains (e.g., Mediterranean, New Zealand, Peru). Due to the coarse-grained, hydraulically-rough and permeable nature of the sediment, gravel beaches are increasingly considered sustainable coastal defences (van Wellen et al., 2000) that can protect low-lying back-barrier regions from flooding, and coastal cliffs from undercutting during storm events. Their societal role is widely acknowledged and coastal engineering structures (seawalls and groins) and management techniques (recharge, recycling and reshaping) are extensively used to maintain and enhance their protective ability (e.g., Moses and Williams, 2008).

It is widely agreed that, compared to sandy beaches, relatively little research has been directed towards understanding the response of gravel beaches to waves (Buscombe and Masselink, 2006; Ivamy and Kench, 2006; Masselink et al., 2010). This is generally ascribed to logistical difficulties associated with making in-situ field measurements of hydro- and sediment-dynamics in these environments, especially during energetic wave conditions. An alternative research methodology, relatively widely used in gravel environments, involves the use of tracers (e.g., Dornbusch et al., 2002; Osborne, 2005; Eikaas and Hemmingsen, 2006; Bertoni et al., 2011; Miller et al., 2011); however, this approach provides only very limited insight into the hydrodynamic forcing. Additionally, gravel beach dynamics can be addressed using controlled laboratory conditions, but, even for experiments labelled ‘proto-type’ (e.g., López de San Román-Blanco et al., 2006; Pedrozo-Acuna et al., 2006; Matias et al., 2012; Turner and Masselink, 2012), wave conditions during testing can at most be considered moderately energetic with maximum significant wave heights of 1 m.

Field measurements of waves, currents and sediment transport on gravel beaches have therefore been limited to relatively calm wave conditions (Chadwick, 1989; Degryse Kulkarni et al., 2004; Austin and Masselink, 2006; Ivamy and Kench, 2006; Curoy et al.,

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2007; Austin and Buscombe, 2008; Masselink et al., 2010). Collectively, these field investigations highlight the importance of swash processes and beach–groundwater interactions. These field studies have further demonstrated that the most prominent aspect of the morphological behaviour of gravel beaches is the dynamic nature of the beach step and the berm in response to changing wave/tide conditions.

It is well established that sandy beaches exhibit alternating phases of onshore and offshore sediment transport, and associated beach profile adjustment, in response to changes in the wave conditions, and that the wave steepness H_0/L_0 is a particularly useful parameter to delineate the different sediment transport regimes (cf., Komar, 1998). There have been very few studies that applied this concept to gravel beach response. Sherman (1991) studied the daily morphological response of two coarse-gravel ($D = 5$–200 mm and 4–64 mm) beaches at Malin Head, Ireland, over a 10-day period with maximum significant wave heights up to 2.5 m and wave periods of 10–11 s. Wave steepness was found to play the key role in controlling onshore ($H_0/L_0 < 0.007$) versus offshore ($H_0/L_0 > 0.01$) sediment transport, and these critical steepness values are similar to those found for sandy beaches. Masselink et al. (2010) collected morphodynamic data from Slapton Sands, a fine-gravel beach ($D =$ 2–10 mm) on the south coast of England, over a 10-day period under a range of wave-tide conditions ($H_s = 0.5$–1 m; $T_s = 4$–8 s; from a nearshore wave buoy). Over the field period, the upper beach experienced accretion and berm formation during tides with low steepness swell waves ($H_0/L_0 < 0.01$), and underwent erosion during tides dominated by high steepness wind waves ($H_0/L_0 > 0.01$).

Wave steepness is, however, not the only factor controlling gravel beach response. Ruiz de Alegria-Arzaburu and Masselink (2010) monitored the bi-monthly morphological response of Slapton Sands over a 2-year period, specifically focussing on storm response ($H_s = 2$–4 m). The vast majority of storms (high wave steepness) caused erosion of the supratidal region, but the intertidal beach response, and the change in overall beach volume, depended strongly on the direction of the storm waves. This suggests that longshore sediment transport processes also play a key role in storm response. Bertoni et al. (2011) monitored storm response of a number of artificial gravel beaches at Marine di Pisa, Italy. Here, the initial beach fills with 8–16 mm gravel were unable to withstand the occasionally very energetic wave conditions ($H_s = 4.5$ m), and sediment was moved offshore. In contrast, beach fills with 30–90 mm gravel responded to extreme storm conditions by exhibiting onshore sediment transport and a 15–19 m landward migration of the berm. So, the sediment size is also a key factor controlling storm response on gravel beaches.

In-situ hydrodynamic measurements during storm conditions on a gravel beach have not been reported in the literature. At best, beach morphology before and after a storm, and offshore wave and water-level conditions for the duration of the storm are available (cf., Ruiz de Alegria-Arzaburu and Masselink, 2010). The paucity of field measurements under energetic conditions on gravel beaches further means that the literature is lacking in relevant tools for calculating wave runup, which is a dominant factor in controlling the potential for overtopping and overwashing, and ensuing morphological modifications to the barrier crest region and flooding of the back-barrier region (Orford et al., 2003). The most frequently cited approaches include those designed for solid structures (van der Meer and Janssen, 1994; Hughes, 2005) or empirically-derived through measurements on sandy beaches (Stockdon et al., 2006). Additionally, Powell (1992) used field data from a range of gravel beach sites to validate extensive physical model results.

Here, we report on detailed measurements of nearshore and inshore wave conditions (to a depth of 10 m local Chart Datum (CD)), wave runup, high-frequency bed-level changes in the swash zone, and supratidal and intertidal morphological response on a fine-gravel beach ($D_{50} = 3.5$ mm; sieve derived) under a range of wave conditions, including energetic events with H_s peaking at 2.5 m. The paper addresses profile evolution and swash dynamics under storm waves in the context of larger scale 3D morphological response with specific focus on beach step and cusp dynamics.

2. Field site

Loe Bar is situated 2 km south-east of Porthleven, Cornwall, UK (Fig. 1) and is an example of a bay-bar which encloses a freshwater lagoon (Loe Pool). The bar itself, perhaps better termed the barrier, represents a 4.3-km long fine-gravel beach ($D_{50} = 2$–4 mm) that extends from Porthleven, to the north, and Gunwallow, to the south (Fig. 1). At its widest point the barrier is 250 m wide between Loe Pool and the sea, and extends 430 m, at its narrowest point between the adjacent headlands, to ~900 m at low water. The contiguous cliffs are composed of Devonian Mylor beds (grey slates) with more resistant schist and quartz outcrops (May and Hansom, 2003). Although there is some sediment supply from the cliffs, the quantities are considered small and this observation is supported by the non-local dominant composition of the beach material (>90% flint; May and Hansom, 2003). The harbour wall at Porthleven and the cliff headland at Gunwalloe create a single sediment cell cut-off from longshore inputs.

Wave statistics from a nearshore directional wave buoy deployed for 1 year in ~15 m CD shows an annual, 10% exceedance and maximum significant wave height H_s of 1.2 m, 2.4 m and 6.1 m, respectively, and a mean wave period T_z of 5.8 s. Orientated at 230° (SW), the site is exposed to dominant energetic waves from the south-west with very limited directional variation (Fig. 1).

3. Methodology

Field measurements were undertaken over a 6-week period between 23 February and 28 March 2012. Presented within this paper are results from topographic surveys undertaken with RTK (real time kinematic) GPS, acoustic bed level sensors (BLS), and headland mounted cameras. In addition to the data presented here complimentary instruments were also deployed; single beam LiDAR; an array of surface and buried pressure transducers and 3 ground water wells, the result of which have been published elsewhere (Almeida et al., 2013; Austin et al., in press).

The main instrument rig consisted of a 70-m long scaffold rig which extended from MHWS to the crest of the bar (Fig. 2) and was instrumented with 45 acoustic bed-level sensors (BLS). The rig was supported by 3 m vertical scaffold poles driven 2 m into the bed across the lower profile. The rig was located primarily above MHWS in anticipation of the large wave conditions that occurred on the 23 February and 24 March. Using the methodology outlined by Turner et al. (2008), the BLS were positioned at 1.5 m intervals for the first 50 m (from the crest) and at 2-m spacing thereafter. The sensors were positioned 1–1.5 m above the bed and operated at a frequency of 95 kHz. Bed-level sensor data were logged at 4 Hz continuously through high tide swash conditions.

Topographic measurements were undertaken every low tide using RTK GPS mounted on a vertical staff with a “flat foot” to ensure surface measurements. Cross-shore profiles were measured through the BLS rig, 5 m north of the rig and 40 m south of the rig, providing comparative cusp embayment and horn profiles, respectively. An all-terrain vehicle (ATV) was used to measure the 3D topography across the barrier: cross-shore and longshore transects were made with the RTK-GPS logging continuously generating an approximately gridded dataset with 5–10 m line spacing (lines were not defined). Point spacing for the profile lines on foot was <3 m, whereas on the ATV sampling was every metre. ATV surveys were undertaken every 2–3 days while conditions were calm and at greater frequency during