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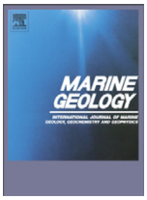

Storm response and beach rotation on a gravel beach, Slapton Sands, U.K.

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ABSTRACT

Continuous Argus video data and fortnightly measurements of subaerial morphology were obtained over a 3-year period from a steep macrotidal gravel beach on the southwest coast of the U.K. Concurrent wave and water-level data were also collected, enabling the correlation of the observed morphological changes to the hydrodynamic forcing. Wave conditions are generally low ($H_s \approx 0.5$–1 m), but the beach is affected by frequent storm wave activity (c. 15 storms per year with $H_s \approx 2$–4 m) with waves either approaching from the south (swell waves) or from the east (wind waves). An assessment of the three-dimensional morphological response of the beach to the two typical storm types was carried out by analysing the impact of 27 storms that occurred from April 2007 to April 2009. Southerly storms cause accretion of the supratidal zone and erosion of the intertidal zone, and a significant loss in overall beach volume. Easterly storms, on the other hand, induce supratidal erosion and intertidal accretion, and a significant gain in overall beach volume. During the intervening calm periods a small supratidal berm is constructed and a modest gain in overall beach volume occurs. Wave modelling indicated that opposing longshore energy fluxes occur for the different storm types with a northerly energy flux during southerly storms and a southerly flux during easterly storms. Weekly shorelines derived from the Argus images revealed that the northern end of the beach widened by c. 30 m and the middle beach receded by c. 40 m over a relatively brief period (a few months). The occurrence of this beach rotation event is attributed to a higher frequency of southerly storms and/or a lower frequency of easterly storms over this period. Thus, the development and stability of the beach on annual time scales depend on the relative contributions of the two storm types, and their sequencing. Longshore sediment transport (LST) rates derived from the data on beach morphological change were compared with several littoral drift formulae previously applied to gravel beaches. The CERC equation, with a proportionality factor k between littoral drift rate I_l and longshore wave energy flux P_l of $k = 0.054$, yielded the best results.

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1. Introduction

Gravel beaches (and barriers) develop where significant amounts of gravel-size material ($D > 2$ mm) are available in the coastal zone. They can be 'pure gravel beaches' when the gravel extends from the storm berm to below low water spring level, 'mixed sand–gravel beaches' with sand and gravel entirely mixed both cross-shore and longshore, or 'composite gravel beaches' characterised by a gravel berm fronted by a sandy low tide terrace (Jennings and Shulmeister, 2002). Gravel beaches are common along formerly (peri-) glaciated coasts, because an abundance of gravel material is generally present in these settings, either derived from erosion of glacial deposits (e.g., Forbes et al., 1991; Shaw et al., 1993; Orford et al., 1996; Isla et al., 1991) or 'scooped-up' from the continental shelf during the Holocene transgression (e.g., Carr and Blackley, 1973; Hails, 1975; Bird, 1996; Long et al., 2006; Plater et al., 2009). Gravel beaches have also been described for localities where the sediment has been supplied by local rivers (e.g., Zenkovich and Schwartz, 1987; Bird, 1996; Shulmeister and Kirk, 1997; Bartholoma et al., 1998) or through cliff erosion (e.g., Jennings et al., 1998; Anthony and Dolique, 2001; Johnston, 2001; Pontee et al., 2004; Pye and Blott, 2009). Regardless of the sediment source and composition, gravel beaches tend to have steep reflective profiles that are characterised by prominent secondary morphological features, such as ridges, berms, step and cusps, but without nearshore bars (Carter and Orford, 1984, 1993; Buscombe and Masselink, 2006).

Short-term (minutes–days) process studies on gravel beaches have focussed on the dynamics of the beach step during tidal cycles and the evolution of the berm over consecutive tides (Kulkarni et al., 2004; Ivamy and Kench, 2006; Austin and Masselink, 2006a; Austin and Buscombe, 2008; Masselink et al., 2010). Over this time scale, tides play a crucial role in controlling where on the beach profile swash processes operate, whereas the wave conditions (wave height, period and direction) dictate the type of morphological response (berm construction/destruction; Masselink et al., 2010). Process studies have also highlighted the importance of swash over surf zone processes (Pedrozo-Acuña et al., 2007) and the role of swash–groundwater interactions (Austin and Masselink, 2006b). Long-term (decennia–millennia) investigations, on the other hand, have

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concentrated on the evolution of gravel barriers under the influence of relative sea-level change and variations in the sediment supply (Orford et al., 2002). These studies have identified the contrasting typologies of swash- and drift-alignment (Orford et al., 1991; Forbes et al., 1995), and have emphasised the transgressive nature of many gravel barriers and the occurrence of overwashing (Orford et al., 1988), or even breaching, during extreme storm conditions (Orford et al., 2003; Pye and Blott, 2009).

There appears to be a distinct gap in the gravel beach/barrier literature with regards to their dynamics over the medium-term (weeks–years). The contrast here with the sandy beach literature is striking: whereas the concept of cyclic (storm and post-storm) and seasonal (summer and winter) morphological change is particularly well established for sandy beaches (cf., Komar, 1998), it is virtually unstudied on their gravel counterparts. The principal reason for this is the lack of observational data of sufficient duration and resolution (temporal and spatial) on gravel beaches. Currently, there are numerous medium-term data sets available from sandy beaches; those obtained using Argus video monitoring (Holman and Stanley, 2007) have been particularly useful in providing unique insights into medium-term nearshore bar and shoreline behaviour (e.g., Ruessink et al., 2000; Quartel et al., 2007; Ojeda and Guillén, 2008). But, no equivalent data are available from gravel beaches, where the data sets, at best, comprise several years of three-monthly or half-yearly beach surveys, supplemented by aerial photographs and event-driven (post-storm) surveys of a small number of cross-shore transects (e.g., Orford et al., 2002, 2003; Pontee et al., 2004; Pye and Blott, 2009).

Here, we describe the results of a 3-year observational study, involving continuous Argus video monitoring and fortnightly RTK-GPS (real time kinematic global positioning system) beach surveys, conducted on Slapton Sands, a 4.5-km long, macrotidal, pure gravel beach on the southwest coast of the U.K. Concurrent wave and water-level data were also collected, enabling the correlation of the observed morphological changes to the hydrodynamic forcing. The overall aim of this paper is to examine the three-dimensional morphological response of Slapton Sands to varying wave conditions. Previous work (Ruiz de Alegria-Arzaburu et al., 2009) has indicated that the study site experiences low-to-medium wave energy conditions ($H_s = 0.5$–1 m) interspersed with frequent storm wave activity ($H_s = 2$–4 m), during which storm waves are either incident from the east (wind waves) or the south (swell). It was found that the beach response depended strongly on the storm wave direction and also varied significantly along the beach for the same storm event, suggesting that longshore as well as cross-shore sediment transport processes are important for redistributing sediments during storm events. The specific objectives of this paper are, therefore, to: (1) quantify, in terms of morphological and volumetric changes, the three-dimensional response of the beach to the two different types of storm conditions, as well as the post-storm recovery process; (2) explain the differing beach responses in terms of cross-shore and longshore sediment transport fluxes; and (3) upscale the findings of this study to discuss the longer-term development and stability of the beach.

2. Study area

Slapton Sands is a 4.5-km long and 80–120 m wide pure gravel ($D_{50} = 2$–10 mm) barrier system located in Start Bay on the southwest coast of the U.K. (Fig. 1). The barrier has a crest elevation of 6–8 m above Ordnance Datum Newlyn (ODN, which is approximately 0.2 m above mean sea level in the U.K.) and is backed by a shallow freshwater lagoon (Slapton Ley). The shoreline is aligned in an approximately north–south orientation, and both the height and width of the barrier increase progressively in a northward direction. The sediment size is highly variable, but the northern end of the beach is consistently finer than the southern end (Buscombe, 2008). However, in comparison to Chesil beach, which is also a pure gravel beach and subjected to a similar wave/tide regime, the lateral grading on Slapton Sands is considerably less pronounced. The well-sorted and fine-gravel composition of the sediments on Slapton Sands is attributed to the closed nature of the sediment system and the fact that the barrier position has remained relatively stable over the last 3000 years, allowing the gravel to be reworked by waves for an extended period of time.

Slapton Sands is the largest of four gravel barriers in Start Bay, the others being Hallsands, Beesands and Blackpool Sands (Fig. 1; despite their names, all barriers are made up of gravel-size material — mainly flint). At high tide, these gravel barriers represent separate environments, but, except for Blackpool Sands, they are connected during spring low tide. Start Bay as a whole can be considered a closed sediment cell: except for some localised cliff erosion, which mainly produces easily erodible fragments of shale, there is no sediment supply to the beaches. A seawall is present at the southern end of Slapton Sands and some minor reshaping of the barrier has occurred in the form of the construction of five gravel 'bastions' placed on the top of the beach in the middle section of the barrier (Fig. 2). The volume of these bastions is approximately 1200 m^3 and they are maintained on an ad hoc basis by 'bulldozing' sediment from the bottom of the beach.

The Start Bay beaches are partly protected from Atlantic swell propagating up the English Channel by Start Point, a prominent headland located 3–4 km to the south of Slapton Sands. Additional shelter is provided by Skerries Bank, a large 'banner bank' comprised of shelly sand (Hails, 1975) that stretches across half of Start Bay from Start Point and has a minimum depth of 5 m ODN. The difference in sediment properties between Skerries Bank and the beaches within Start Bay suggests that there is no sediment exchange between the bank and the gravel beaches. The lack of sediment exchange between Skerries Bank and the beaches is further suggested by the large water depth (>15 m), considerably larger than the depth of closure estimated at 10 m, separating the bank from the shoreline. Slapton Sands is exposed to a low-to-medium energy wave climate (mean $H_s = 0.5$–1 m; storm $H_s = 2$–4 m; Ruiz de Alegria-Arzaburu et al., 2009), comprising a mixture of southerly swell and easterly wind waves (see wave rose in Fig. 1). Due to the shelter provided by Start Point and Skerries Bank, the most energetic wave conditions are due to wind waves from the east, but large southerly swell waves are also able to refract into Start Bay and affect the beach. The tidal regime is macrotidal with spring and neap ranges of 4.3 m and 1.8 m, respectively (Admiralty Tide Tables, 2009). The 1:50 storm surge level in the region is 0.5 m (Lowe and Gregory, 2005) and the current relative sea-level rise is estimated at 2.5 ± 0.7 mm per year based on measurements from 1962 to 2004 (Haigh et al., 2009).

There is strong evidence to suggest that 5000–8000 years ago, with sea level 5–15 m below present, a chain of barrier islands extended across Start Bay (Hails, 1975). The barrier island chain was dissected by tidal inlets that allowed for the mixing of salt and fresh water in the lagoon behind the barriers. As sea level continued to rise, albeit at a slackening pace, the barrier chain became divided by smaller headlands and formed separate beaches. About 3000 years ago the Start Bay beaches, including Slapton Sands, reached more or less their present position and the brackish water lagoon behind the chain of barrier islands had developed into a freshwater lagoon (Morey, 1983). The transgressive nature of Slapton Sands has been confirmed by a number of cores through the barrier which have demonstrated that the gravel material is underlain by salt marsh and peat deposits (Massey and Taylor, 2007). Additionally, after severe storms, peat can be found exposed in the intertidal zone of Hallsands, the southernmost gravel barrier in Start Bay.

Significant damage has occurred on Slapton Sands over the last decades during storms due to flooding and barrier overwash. As an example of the extent of the damage of these events over the past few years, in January 2001 an easterly storm undercut a section of the

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