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A new parameterisation for runup on gravel beaches

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ABSTRACT

Video derived runup statistics from ten separate deployments at six field sites have been used to develop a new parameterisation for the prediction of runup of runup on gravel beaches. These data were collected over a 2-year period under energetic storm conditions with significant wave heights of $H_s = 1$–8 m from gravel beaches and barriers composed of fine gravel ($D_{50} = 2$ mm) to large pebbles ($D_{50} = 160$ mm). An additional data set was generated using the numerical model XBeach-G, developed specifically for gravel beaches, and this synthetic dataset was used to further explore the role of hydrodynamic and morphological parameters on wave runup. A runup equation was developed using the synthetic data set and validated using the field data. The four parameters in this equation are, in decreasing order of importance, significant deep water wave height (H_s), spectral mean period ($T_{m-1,0}$), beach slope ($\tan\beta$) and grain size (D_{50}). The new gravel beach runup equation was found to fit the synthetic data set and the field data extremely well ($r^2 = 0.97$ and 0.89, respectively) and the new equation performs significantly better than existing runup equations, even those specifically developed for gravel beaches.

1. Introduction

Gravel beaches and barriers are large morphodynamic features that are common along many formerly glaciated and para-glaciated coasts (e.g., northern Europe, Canada) and along coasts backed by high mountainous terrain where gravel is supplied by local rivers (e.g., Mediterranean, New Zealand). Composed of coarse sediment (D_{50} > 2 mm), the beaches generally support steep profiles ($\tan\beta > 0.1$) and, in the absence of cliffs, are often backed by low-lying land, freshwater lagoons and/or estuaries. While reflective gravel beaches provide an effective coastal defence during elevated water levels and storm conditions, and are considered sustainable forms of coastal defence (e.g., Johnson, 1987; Aminti et al., 2003), they can undergo rapid and large-scale changes in their morphology (Orford et al., 2003). While complete barrier breakdown is rare, the characteristic, low-lying back barrier region can suffer rapid inundation under such conditions, and this can be of significant concern for coastal managers.

The morphological response of gravel beaches to changes in extreme hydrodynamic forcing has been well studied (Orford et al., 1991; Orford et al., 2003) and storm response can be grouped into four main regimes – swash, overtopping, overwashing and breaching – which represent increased wave, water level and runup conditions. The main controlling aspect of barrier response is the elevation difference between the runup and the barrier crest, which is known as 'freeboard'. When the runup level does not exceed the crest of the gravel barrier (i.e., positive freeboard), the seaward face of the beach will be subjected to energetic swash processes that can significantly alter the beach morphology, but leaves the crest untouched (Ruiz de Alegria-Arzaburu and Masselink, 2010). As the runup level starts to exceed the crest level (i.e., negative freeboard), sediments get transferred from the front of the barrier to the barrier crest and sediment deposition can lead to vertical accretion of the crest in a process termed overtopping (Orford and Carter, 1982). As the runup level and swash flows increase even more, overtopping is replaced by overwashing, resulting in sediment deposition on the landward slope of the beach/barrier (Orford et al., 1991). Sediment can be sourced from the barrier crest, leading to lowering of the barrier crest which enhances overwashing even more through positive feedback (Matias et al., 2012). Continued overwash, on the shorter term as a result of a very extreme event with large negative freeboard and on the longer-term aided by sea-level rise, can lead to barrier rollover (landward migration of the barrier system) or even barrier break-down (Orford et al., 1991). Barrier morphology, sediment characteristics (composition, permeability, sediment availability) and forcing conditions all influence the rate of barrier migration and the long-term barrier resilience.

During the 2013/2014 winter, the southwest coast of England experienced several extreme storm events that resulted in barrier overwash at several sites, including Chesil Beach and Hurst Spit in Dorset, Slapton Sands and Westward Ho! in Devon, and Loe Bar in Cornwall (Masselink et al., 2015). The key factors controlling the occurrence of overwashing is the maximum runup level, which is summation of tide, storm surge and wave runup; therefore, the ability to predict runup due to waves is a very useful coastal engineering application. Accurate estimation of

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runup provides increased capabilities for vulnerability assessment and also assists with the effective design for nourished gravel beaches (Stripling et al., 2008).

The logistical challenge of measuring wave runup on gravel beaches, especially under energetic wave conditions, has meant that sandy beaches have been the main focus for field observations of wave setup and runup over the last decades (e.g., Guza and Thornton, 1982; Holman, 1986; Nielsen and Hanslow, 1991; Ruessink et al., 1998; Ruggiero et al., 2001; Stockdon et al., 2006). Field studies have been undertaken using a range of methodologies, including in-situ logging using resistance runup wire (Holman and Guza, 1984) and remote techniques involving video cameras (Holman and Sallenger, 1985). Such observations have formed the basis for formulating equations for predicting runup extent and behaviour on beaches (Holman and Sallenger, 1985; Stockdon et al., 2006) and solid structures (Van der Meer and Janssen, 1994; Hughes, 2004). One of the most commonly cited and effective predictors for sandy sites is by Stockdon et al. (2006), who used data from a range of reflective to dissipative beaches to develop an empirical parameterisation for runup based on wave height, wave period and beach gradient. This equation is widely used for predicting the overwash potential on and vulnerability of sandy barrier islands during extreme storm events (e.g., Stockdon et al., 2007). While Stockdon et al. (2006) provides formulae for more reflective sites, no data from gravel beach sites was included in the development of the runup equation. Application of the Stockdon et al. (2006) equation to several gravel beach sites in the UK suggests that wave runup on gravel beaches under energetic wave conditions is significantly under-predicted by the equation (Masselink et al., 2015), although the equation did perform quite well in a large scale flume experiment involving a gravel barrier forced with relatively calm conditions (Matias et al., 2012).

The unsatisfactory application of sandy beach runup formulae to gravel beaches is a reflection of some fundamental differences in morphodynamics between beaches made of sand and gravel (Buscombe and Masselink, 2006). The most important difference is related to the steeper profile of gravel beaches and their ability to maintain a reflective profile under extreme wave conditions (Hughes and Cowell, 1987) through adjustments to the beach step (Austin and Masselink, 2006; Austin and Buscombe, 2008; Ivamy and Kench, 2006). This difference becomes especially relevant under energetic wave conditions. On sandy beaches, runup under extreme wave conditions becomes dominated by infragravity waves (Guza and Thornton, 1982; Holman and Sallenger, 1985; Ruessink et al., 1998; Ruggiero et al., 2001; Stockdon et al., 2006; Senechal et al., 2011) with the incident storm waves simply breaking and dissipating their energy further offshore, whereas on gravel beaches very large waves can directly impact on the beach (Fig. 1). It is important in this context to distinguish between the three major types of gravel beaches, as identified by Jennings and Shulmeister (2002). Both the ‘mixed sand and gravel’ and ‘composite gravel’ beach types are likely to develop a dissipative surf zone under energetic wave conditions; however, the ‘pure gravel’ beach type is the one most likely to retain its reflective status during storms.

There are runup equations specifically derived for gravel beaches. In the UK, Powell (1990) used field measurements of gravel beaches in combination with a physical model to develop a runup predictor for gravel beaches. However, while the Powell (1990) equation is designed for gravel sites, the beach slope is represented only through the sediment size, potentially limiting its use. More recently, Polidoro et al. (2013) used field measurements on gravel beaches to develop an improved runup formula, but these were quite specific to the beaches along the southeast coast of England where mixed sand and gravel beaches are dominant and a bimodal wave climate prevails. The equation by Polidoro et al. (2013) also requires a large number of wave parameters that are not always available, making it less straightforward to use. Neither the Powell (1990) nor Polidoro et al. (2013) equations have been developed using extreme wave conditions and their application to very large waves ($H_s > 5$) would require extrapolating their use beyond conditions for which they were developed.

In summary, there is a lack of field measurements of wave runup on gravel beaches under energetic waves and such data are required to develop robust runup predictors specific to such environments and conditions. This paper addresses this lack by presenting field data collected from six gravel-dominated field sites ($D_{50} = 2$–150 mm) during ten periods of energetic conditions ($H_s = 1$–8 m) with the principal aim to propose a new runup parameterisation specific to (pure) gravel beaches. We will first describe the methods employed during these field campaigns and the processing undertaken to derive runup statistics, and compare these with existing runup formulations. We then use the numerical model XBeach-G (McCall et al., 2014; Masselink et al., 2014; McCall et al., 2015a), a gravel-specific development of the XBeach model (Roelvink et al., 2009), to firstly compare our field data to the XBeach-G model and then use the model to generate synthetic data to extend and explore the parameter space beyond that represented in the field. Both field data and synthetic data are also compared to existing runup formulations. A new wave runup equation is then developed from the XBeach-G data and validated using the field data.

2. Methodology

2.1. Field sites

The collection of in-situ runup datasets and corresponding morphological response was undertaken at six gravel beaches across southern

Fig. 1. Wave breaking directly on Chesil beach during storm on 5 February 2014; the flow just landward of the large collapsing breaker is best described as backwash. (photo by Richard Broome, reproduced with permission).