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Detailed investigation of overwash on a gravel barrier

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ABSTRACT

This paper uses results obtained from a prototype-scale experiment (Barrier Dynamics Experiment; BARDEX) undertaken in the Delta flume, the Netherlands, to investigate overwash hydraulics and morphodynamics of a prototype gravel barrier. Gravel barrier behaviour depends upon a number of factors, including sediment properties (porosity, permeability, grain-size) and wave climate. Since overwash processes are known to control short-term gravel barrier dynamics and long-term barrier migration, a detailed quantification of overwash flow properties and induced bed-changes is crucial. Overwash hydrodynamics of the prototype gravel barrier focused on the flow velocity, depth and discharge over the barrier crest, and the overwash flow progression across and the infiltration through the barrier. During the BARDEX experiment, overwash peak depth (0.77 m), velocity (5 m s^{-1}) and discharge (max. 6 m^3 m^{-1}) were high, especially considering the relatively modest wave energy (significant wave height = 0.8 m). Conversely to schemes found in the literature, average flow depth did not linearly decrease across the barrier; rather, it was characterised by a sudden decrease at the crest, a milder decrease at the barrier top and then propagation as a shallow water lens over the backbarrier. The barrier morphological evolution was analysed over a series of 15-min experimental runs and at the timescale of individual overwash events. Overall, the morphological variation did not result from an accumulation of many small consistently erosive or accretionary events, but rather the mean bed elevation change per event was quite large (10 mm) and the overall morphology change occurred due to a small imbalance in the number of erosive and accretionary events at each location. Two relationships between overwash hydrodynamic variables were deduced from results: (1) between overwash flow depth and velocity a power-type relation was obtained; and (2) a linear relation was observed between overwash flow depth and maximum overwash intrusion distance across the barrier top (i.e. overwash intrusion). Findings from this study are useful to enhance the knowledge of overwash processes and also have practical applications. On the one hand, results shown here can be use for the validation of overwash predictive models, and additionally, the simple empirical relations deduced from the dataset can be used by coastal managers to estimate overwash intrusion distance, which in turn can assist in the location of areas under risk of overwash and breaching.

1. Introduction

Gravel beaches are widespread on the wave-dominated coastlines of Northern Europe, Canada, USA, Japan, New Zealand and Latin America (Buscombe and Masselink, 2006), and develop in a variety of settings where sediment supply and wave energy favour the accumulation of coarse sediments in the shore zone (Orford et al., 2002). Overwash plays an important role in the evolution of gravel barrier beaches causing them to migrate inland over time by the 'rollover' mechanism (e.g., Orford and Carter, 1982; Carter and Orford, 1993). This mechanism involves onshore-directed sediment transport driven by storm waves through erosion from the front of the barrier, transfer across the barrier crest and deposition at the back of the barrier in the form of washover deposits. By controlling the rate and spatial pattern of gravel barrier rollover, storm waves have been regarded as driving short-term (annual to decadal) gravel barrier migration (Orford et al., 1995). Overwash can also contribute to other patterns of gravel barrier evolution, such as breaching (Bray and Duane, 2001), barrier breakdown (Pye and Blott, 2009), outlet formation (Hart, 2007) and outlet closure (Orford et al., 1988).

Despite the importance of overwash in determining the dynamic behaviour of gravel beaches, field measurements of overwash are scarce. Important field studies on this subject are reported by Orford et al. (1999), Lorang (2002), Orford et al. (2003) and Bradbury et al. (2005), and in the laboratory by Obhrai et al. (2008). Overwash mainly occurs during storms and accurate field measurements are therefore hazardous and difficult to obtain. Overwash sediment transport in sandy beaches has been measured using pre- and post-storm surveys (e.g., Guillén et al., 1994; Stone et al., 2004), and evaluated with ground photographs and vertical or oblique aerial photographs (e.g., Rodríguez et al., 1994; Cleary et al., 2001). In-situ measurements of gravel barrier

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overwash sediment transport are very hard to obtain, and are potentially hazardous to people and equipment. Therefore, large-scale flume experiments can provide a valuable complement to field datasets. Although many laboratory experiments have been conducted of sediment transport in the swash or surf zone, only a handful of experiments on overwash have been conducted (Hancock and Kobayashi, 1994; Donnelly, 2008; Obhrai et al., 2008; Alessandro et al., 2010; Kobayashi et al., 2010; Park and Edge, 2010; Figlus et al., 2011), including the Barrier Dynamics Experiment (BARDEX) reported here (Williams et al., 2012). During BARDEX, overwash was simulated with waves that reached 1.0 m at breaking (Matias et al., 2012) and thus were significantly larger than those used in previous laboratory experiments, where wave heights were 0.14–0.33 m. Details about overwash thresholds based on the BARDEX experiment can be found in Matias et al. (2012).

In this work, the overwash simulations completed in Test Series E of the BARDEX experiment (Matias et al., 2012; Williams et al., 2012) are described. Results are presented from two perspectives: (1) the Eulerian perspective where overwash hydraulic variables and associated morphological changes are measured at the barrier crest, which represents the location that defines the transformation from swash to overwash; and (2) the Lagrangian perspective where high-intensity overwash flows and barrier properties are measured across the barrier. To collect data on overwash characteristics and bed changes, a large array of acoustic bed-level-sensors was deployed to collect bed/water surface elevation data at 4 Hz (cf., Turner et al., 2008). The obtained high-frequency data allowed overwash to be analysed on an event-by-event scale to provide valuable insight into overwash behaviour over a gravel barrier. The primary objectives of this paper are to: (1) provide a data-set of overwash hydraulics on gravel barriers; (2) improve and develop empirical relations between key parameters of overwash flow; and (3) gain insight about how overwash evolves across the backbarrier.

2. Experimental setup and methods

Experiments to study gravel barrier overwash were undertaken at proto-type scale in the Delta Flume (The Netherlands) during the BARDEX project (Williams et al., 2012). A gravel barrier (35 m long, 5 m wide and 4 m high) composed of sub-rounded gravel ($D = 11$ mm) was constructed in the flume with the mid-barrier crest located at a distance of 95 m from the wave paddle (Fig. 1). The beach profile used at the BARDEX experiment was loosely based on Slapton Sands, Devon, England (Austin and Masselink, 2006).

Overwash was studied by exposing the barrier to variable wave and water-level (h_s) conditions (Test Series E1 to E10; cf. Matias et al., 2012); however, for the purpose of this study, only Test Series E10 will be considered because only during this series did frequent backbarrier overwash occur. Test Series E10 consisted of eleven 15-min runs in which the water level ($h_s = 3.75$ m), peak wave period ($T_p = 8$ s), significant wave height ($H_s = 0.8$ m) and wave sequence were kept constant to study the behaviour of the barrier under fully-developed overwash conditions. All wave conditions conformed to a JONSWAP spectrum, specified by H_s and T_p.

Barrier morphology was surveyed before and after each run using a roller and actuator which followed the bed profile from an overhead carriage (Fig. 1d). The sub-aerial barrier was monitored continuously at 4 Hz using acoustic bed-level sensors (BLS) deployed at 0.5-m spacing (Fig. 1e) and approximately 1 m above the bed. These sensors are described in detail in Turner et al. (2008) and were also used by Masselink and Turner (2012) to investigate swash dynamics during BARDEX non-overwash runs. When mounted perpendicular to the bed, the sensors use the time of flight of the reflected signal to obtain non-intrusive Eulerian measurements, with an accuracy of c. 1 mm of the vertical distance to the closest target: the sand level when the bed is "dry", and the water level when the bed is submerged (Blenkinsopp et al., 2011). A more detailed analysis of BLS data was undertaken for Test Series E10A, E10B and E10C because during those series full overwash and significant deposition occurred on the sub-aerial back-barrier where the BLS were located.

In this study, an overwash event is defined as a single passage of water above the barrier crest; therefore, during the test runs a number of overwash events are recorded at each BLS position. BLS records were pre-processed to separate overwash events and bed-level events, which are measured by the variation in bed elevation before and after the overwash event. For all BLS positioned landward of the beach (BLS32 to BLS 44; Fig. 1), every overwash event was identified and isolated. For each overwash event, maximum and average depth, skewness of the water depth distribution and duration of the event were computed.

Based on various morphologic and hydrodynamic parameters, Matias et al. (2012) defined the Overwash Potential (OP, Eq. (1)) as a parameter for quantifying the likelihood of overwash, as well as providing an estimate of the overwash water level relative to the barrier crest elevation:

$$\mathrm{OP} = \left[1.1\left(0.35\tan\beta(H_0L_0)^{0.5} + \left(\left[H_0L_0\left(0.563(\tan\beta)^2 + 0.004\right)\right]^{0.5}/2\right)\right)\right] + \eta - h_c \tag{1}$$

where $\tan\beta$ is the beach slope, H_0 is the offshore wave height, L_0 is the offshore wave length, η is the sea level, including astronomical tides and storm surge, and h_c is the barrier crest elevation. The first term of the equation (in square brackets) is the 2% exceedence for the vertical runup predicted by Stockdon et al. (2006). The position and elevation of the barrier crest were determined at the end of the runs, whereby the crest was defined as the location of the profile with the maximum elevation. Beach slope was calculated for the barrier section between mean water level and the top of the beach, where a break in slope was typically observed.

Overwash velocity was calculated following two methods: leading edge and continuity. The leading edge velocity represents the velocity obtained using the time delay between the leading edge of the overwash water between two BLS positions. Because overwash leading edge velocities can be very fast (>5 m s^{-1}; Matias et al., 2010) and the BLS sensors record at 4 Hz and are spaced at 0.5 m, the leading edge of the overwash often arrives at two successive BLS positions at the same time. Therefore, the leading edge velocity at the crest was computed between BLS30 and BLS33 (before and after the crest position, 1.5 m apart; Fig. 1) to obtain an average value for the barrier crest area. The second methodological adjustment is the use of the interpolated timing of water depth = 0.02 m. The definition of 2 cm as the leading edge is somewhat arbitrary; however, this water depth has been used in coastal engineering applications (e.g., Pullen et al., 2007). Alternative measurements of the velocity close to the overwash leading edge were obtained using the volume continuity method described in Blenkinsopp et al. (2010). In brief, this technique computes a depth-averaged flow velocity based on the local depth and the rate of change of flow volume landward of the point of interest. Obtaining Eulerian estimates of the depth-averaged flow velocity throughout the duration of each overwash event using continuity requires the assumption that there is no infiltration into the bed. This assumption is clearly invalid when considering a gravel barrier beach and as such the technique has only been used to obtain initial flow velocities immediately after arrival of the overwash leading edge when infiltration is expected to be limited.

The maximum distance across the barrier top and backbarrier that overwash water reaches inland is here termed overwash intrusion, and was calculated for every overwash event. Exact overwash intrusion is impossible to measure with sensors at discrete locations, as intrusion is likely to be located somewhere between two consecutive BLS. Therefore, intrusion was interpolated using the overwash depth progression over the last two sensors. The distribution of overwash intrusions is