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Measurements of morphodynamic and hydrodynamic overwash processes in a large-scale wave flume

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ABSTRACT

Overwash is an important process that controls short-term barrier dynamics, as well as long-term barrier migration, but this process is difficult to study in the field due to its rare occurrence and the challenging conditions under which it occurs. This paper uses data collected during the BARDEX II experiment in the Delta Flume, the Netherlands, where a proto-type barrier was subjected to a range of wave and water level conditions. The objectives of this research are to: (1) compare the morphologic response to overwash on a gravel barrier (BARDEX 2008 experiment) with that on a sandy barrier (BARDEX II); (2) understand the influence of wave period on overwash characteristics and sediment transport; and (3) improve current knowledge of overwash hydrodynamics. The comparative analysis shows that barrier overwash can be affected by negative feedback that stabilises the barrier through barrier crest accretion on gravel barriers, and by submerged bar development on sandy barriers. An increase in the wave period induced a reduction in overwash frequency over the crest, but no significant relation was found between wave peak period and overwash discharge. Nevertheless, overall water discharge during an overwash episode significantly correlates with overall overwash sediment transport rate. Overwash flow depths during the experiment were relatively shallow and velocities were similar compared to those measured during previous studies and reported in the literature. Despite the controlled laboratory conditions, collection of reliable and accurate measurements of overwash velocities remains challenging.

1. Introduction

Overwash is a natural process that results from a singular combination of oceanographic and coastal geomorphologic conditions. Factors controlling the frequency and intensity of overwash, and the resulting morphologies include oceanographic conditions (e.g., Fisher et al., 1974), the orientation of a coast relative to a storm (e.g., Fletcher et al., 1995), nearshore bathymetry (e.g., Houser, 2012), beach topography (e.g., Leatherman, 1976), back-beach elevations (e.g., Morton and Sallenger, 2003), dune morphology (e.g., Donnelly and Sallenger, 2007), engineering structures (e.g., Hayden and Dolan, 1977), location and orientation of footpaths and roads (e.g., Nordstrom and Jackson, 1995), and shorefront infrastructures (e.g., Hall et al., 1990).

Overwash occurs both on sand and gravel barriers. Field studies of overwash in sandy environments are more common (e.g., Holland et al., 1991; Leatherman, 1976; Matias et al., 2010; Priestas and Fagherazzi, 2010) than on gravel beaches. Overwash sediment transport on sandy beaches has been measured using pre- and post-storm traditional surveys (e.g., Guillén et al., 1994; Stone et al., 2004) or Lidar surveys (e.g., Sallenger et al., 2006; Stockdon et al., 2009), and has been evaluated with ground photographs and vertical aerial photographs (e.g., Cleary et al., 2001; Rodríguez et al., 1994). Important field studies on gravel barriers are reported by Orford et al. (1999, 2003), Lorang (2002) and Bradbury et al. (2005).

Overwash mainly occurs during storms when accurate in-situ field measurements are hazardous and difficult to obtain. Laboratory experiments on overwash provide numerous advantages in relation to fieldwork, including the ability to control the hydrodynamic conditions to ensure overwash occurs as well as logistical benefits (more preparation time, capacity to recruit researchers, less stressful schedules, simplification of equipment installation and power supply and provision of a safe environment for people and equipment). Investigations in small-scale physical models can be used to study coastal processes using well established scaling laws, but shortcomings due to scale effects remain and are not well understood (Van Rijn et al., 2011). Several small-scale experiments on overwash have been undertaken by: Hancock and Kobayashi (1994); Obhrai et al. (2008), Donnelly (2008),

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Kobayashi et al. (2010), Park and Edge (2010), and Figlus et al. (2011). Scaling problems can be overcome when a large-scale facility is used for quantifying physical processes that are almost impossible to measure in nature (Dette et al., 2002). Therefore, large-scale experiments can provide a valuable complement to field datasets (D'Alessandro et al., 2012; Tomasichio et al., 2011). Large-scale experiments on overwash have been undertaken during the Barrier Dynamics Experiment (BARDEX 2008) reported by Williams et al. (2012). During BARDEX 2008, overwash was simulated with waves that reached 1.0 m at breaking (Matias et al., 2012) and thus this experiment was at a significantly larger scale than previous laboratory experiments, where wave heights were in the range 0.14 m (Park and Edge, 2010) to 0.33 m (D'Alessandro et al., 2010).

Repeated overwash processes are important for long-term natural evolution of transgressive barrier islands, whereby the net volume of sand contained in the barrier structure is often maintained, but environments translate landwards (e.g., Dolan and Godfrey, 1973). Overwash processes may reinforce or disrupt barrier resilience; this is partly a function of barrier-lithosome volume, which determines the amount of sediment that needs to be eroded before a critical state is reached, and thus provides a buffering effect (Masselink and van Heteren, 2014).

Sandy beaches are affected by storms in different ways, depending on the character of the storm and the morphology of the beach. Sallenger (2000) defined four classes or regimes: swash regime, collision regime, overwash regime and inundation regime. The overwash regime can even be refined in to overtopping and overwash. Orford and Carter (1982) established that overtopping is characterised by crest accretion and an increase in crest elevation; and overwash is characterised by a lowering of the crest by erosion and formation of washover deposits landwards of the crest.

In this work, overwash simulations during the BARDEX II experiment (Blenkinsopp et al., 2016) are described. The first objective of this research is to compare the morphologic response of a gravel barrier (BARDEX 2008 experiment) and a sandy barrier (BARDEX II experiment) to overwash, including differences in feedback mechanisms and barrier resilience. The second objective is to assess whether elevated water levels with shorter period waves or lower water levels with longer period waves are more important to barrier evolution. The first tends to produce high frequency overwash flows and the latter tends to generate less frequent overwash flows. The third objective is to improve current knowledge of in-situ overwash hydrodynamics.

2. Experimental setup and methods

2.1. Experimental setup

Experiments to study sandy barrier overwash were undertaken at prototype-scale in the Delta Flume (The Netherlands, Fig. 1) during the BARDEX II project (Masselink et al., 2016). A barrier (75 m long, 5 m wide and 4.5 m high, Fig. 1) was constructed in the flume using medium-size sand (median = 1.2 ϕ; 0.43 mm), with the mid-barrier crest located at a distance of 100 m from the wave paddle (Fig. 1). The sand barrier was separated from the lagoon by a permeable wall to allow water to move freely between the back-barrier slope and the lagoon, but prevent the ingress of sand into the lagoon during overwash tests.

Overwash was studied by exposing the barrier to variable wave and water-level conditions. Test Series D consisted of seven sequences (D1 to D7; Table 1), each comprising a number of 20-min wave runs. During each series, the water depth at the wave paddle (h_s) was gradually increased in 0.15 m steps to achieve a sequence of swash – overtopping – overwash. Significant wave height (H_s) remained constant at about 0.8 m and peak wave period (T_p) ranged from 4 s to 10 s (Table 1). In Test Series E the morphological response of the barrier under fully developed overwash conditions was investigated. Each run during Test Series E lasted 13 min with sea level and waves were kept as constant as possible (Table 1). All wave conditions conformed to a JONSWAP spectrum, specified by H_s and T_p.

All our observations are in the overwash regime on the storm impact scale of Sallenger (2000). The differentiation between overtopping and overwash on morphological response as suggested by Orford and Carter (1982) was not noticeable during the course of the experiment. Therefore it was considered that a run measuring overtopping would be dominated by shallow water depths over the barrier crest with limited water intrusion after the crest (Fig. 1a); whilst runs measuring overwash would be dominated by larger water quantities passing by the crest (Fig. 1b).

2.2. Morphological measurements

Barrier morphology was surveyed before and after each run using a roller and an actuator which followed the bed profile from an overhead carriage (Fig. 1), thereby allowing profile measurement of both the sub-aerial and submerged parts of the beach. The position and elevation of the barrier crest (h_{crest}) was determined at the end of each run, whereby the crest was defined as the location on the profile with the maximum elevation above flume floor (z maximum). Beach slope ($\tan\beta$) was calculated for the barrier section between mean water level and the upper limit of the beach face.

The sub-aerial barrier was monitored at 4 Hz using acoustic bed-level sensors (BLS) deployed at 0.5-m spacing (Fig. 1d) and approximately 1 m above the bed. These sensors are described in detail in Turner et al. (2008) and were also used by Matias et al. (2014) to investigate overwash dynamics during BARDEX 2008. Detailed analysis of BLS data was undertaken for runs D18, D25, D34, D44, D53, D64, D74, and E1–E5 for which repeated overwash and significant water depths were measured by BLS array.

During overwash, even slight alongshore variations in elevation lead to overwash flow convergence, often resulting in the development of a scour channel at the back of the barrier which acted as a conduit for landward sediment transport. To avoid this channel back-cutting up the barrier crest over successive runs and thereby affecting wave run-up at the front of the barrier, the backbarrier morphology was manually reconstructed after each run by filling in the scour channel and levelling the barrier top and backbarrier slope. The vertical retaining wall that was used to separate the barrier from the lagoon (Fig. 1c) reduced the available space to accommodate overwash sedimentation and retained the part of the overwash water that reached the backbarrier. Despite the pumps used to transfer water from the backbarrier to the 'sea' operating at full capacity, pooling of water occurred in the backbarrier region. The bed profiler also could not survey the backbarrier region because of an instrumentation carriage located above this region of the flume. Therefore, only the foreshore and barrier top morphologies, up to $x = 110$ m, are considered during the overwash experiments. Due to this limitation, the overwash/overtopping sedimentation volume was determined indirectly. The pre- and post- morphological profiles measured with the profiler were subtracted for the region seawards and landwards of the barrier crest. Because the flume is a closed system, all sediment eroded from the region seawards of the barrier crest was attributed to overwash/overtopping sedimentation landwards of the barrier crest. The sediment transport rate ($m^3m^{-1}min^{-1}$) was obtained considering the duration of each run (20-min and 13-min, for Test Series D and E, respectively).

Beach morphodynamic parameters were computed: the Iribarren number (ξ, Eq. (1)) and the surf scaling parameter (ε, Eq. (2)).

$$\xi = tan\beta/\left(\sqrt{H_s/L_0}\right) \tag{1}$$

$$\varepsilon = a\, w^2/(g\, tan^2\beta) \tag{2}$$