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Intra-swash hydrodynamics and sediment flux for dambreak swash on coarse-grained beaches

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ABSTRACT

The paper reports on dambreak-type swash experiments in which intra-swash hydrodynamics and sediment flux are measured for swash on a coarse sand beach and a gravel beach. Flow velocity and depth are measured using PIV and LIF respectively; the intra-swash sediment flux is measured using sediment traps. Comparison of measured hydrodynamics with the immobile, permeable bed experiments of Kikkert et al. (2013) indicates that bed mobility impacts on the swash hydrodynamics, reducing the maximum run-up by approximately 8% for both beaches, compared to the maximum run-up on the corresponding immobile beach. The measured intra swash sediment flux at a given location is characterised by high flux at the moment of bore arrival, followed by rapid decay during uprush, becoming zero at some time before flow reversal. For the gravel beach, the backwash sediment flux is negligibly small, while for the sand beach the backwash flux increases slowly as the flow accelerates down the beach, and peaks at about the time of maximum backwash velocity. Intra-swash sediment flux calculated using the Meyer-Peter and Müller bed load transport formula, with measured hydrodynamics as input and bed shear stress estimated using both the Swart and Colebrook formulae, is within a factor 2 of the measured intra-swash flux. The agreement between the calculated and measured flux is better for the sand beach than for the gravel beach, and better for uprush than for backwash. For the sand beach there is good agreement between calculated and measured total uprush and total backwash sediment volumes. The agreement is less good for the gravel beach, for which calculated and measured uprush volumes show a similar trend but the calculated backwash volumes over-estimate the (negligible) volumes observed in the experiments.

1. Introduction

Swash on steep, coarse-grained beaches is generated by the collapse of wave bores on the beach slope, resulting in high flow velocities with potential for substantial sediment flux and morphological change. Hydrodynamics and sediment dynamics within a swash event are complex because of the highly turbulent and aerated nature of the collapsing bore and the high unsteadiness and non-uniformity of the flow across the swash zone. In field conditions the complexity is augmented by interactions between swash events of varying magnitude and duration, caused by the varying period and amplitude of the incident waves, and by the effects of low-frequency water surface oscillations in the surf and swash zones.

Field experiments investigating swash hydrodynamics and sediment dynamics have developed substantially over the last two decades in terms of the sophistication of the instruments deployed and the degree to which detailed processes are captured by the measurements. Regarding sediment flux, sediment trapping has been used to measure total uprush and total backwash transport volumes (Hughes et al., 1997; Masselink and Hughes, 1998; Austin and Masselink, 2006; Masselink et al., 2009) and high-resolution bed elevation measurements across the swash zone have been used to obtain net sediment transport volumes for individual swash events (e.g. Blenkinsopp et al., 2011). These measurements are extremely valuable in terms of quantifying sediment fluxes and morphological change for swash events in the field. However, they do not provide a complete picture since they reveal little (in the case of traps) or nothing (in the case of bed elevation measurements) of the sediment flux during a swash event. In principle, measurements of intra-swash sediment flux can be obtained from co-located measurements of velocities and concentrations, but obtaining these measurements sufficiently accurately over the complete water column to give total sediment flux through the full swash cycle remains a significant practical challenge (Blenkinsopp et al., 2011).

In the laboratory, small-scale wave flumes have been used to study swash hydrodynamics over immobile, impermeable beaches (e.g. Petti and Longo, 2001; Cowen et al., 2003; Gedik et al., 2005; Shin and Cox, 2006; Sou et al., 2010; Rivillas-Ospina et al., 2012). Large-scale wave

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flume experiments have studied sand suspension processes in the swash zone (Alsina and Caceres, 2011; Caceres and Alsina, 2012), interactions between surf and swash bed dynamics (Alsina et al., 2012), the effects of long waves, wave groups and random waves on surf and swash bed dynamics (Baldock et al., 2011) and beach groundwater effects on swash sediment transport (Masselink and Turner, 2012). These have yielded insights into swash zone sediment processes and morphology, but, as for field experiments, estimates of swash sediment transport are either inferred from bed elevation measurements or are limited to suspended sediment flux based on co-located velocity and suspended sediment concentration measurements. More recently, van der Zanden et al. (2015) and Puleo et al. (in press) obtained measurements of intra-swash sediment concentrations and velocities within the sheet-flow layer of swash in large-scale wave flume experiments. The studies used conductivity-based instrumentation for the concentration measurements; for the sheet-flow velocities, Puleo et al. (in press) used an acoustic velocity profiler while van der Zanden et al. (2015) cross-correlated concentration measurements from a pair of concentration probes horizontally separated by 15 mm. Neither method was successful in fully resolving the velocities through the sheet-flow layer and through the whole swash cycle. Nevertheless, Puleo et al. (in press) combines their sheet-flow results with concentration and velocity measurements above the sheet-flow layer to estimate the relative contributions of suspended load and sheet-flow load to the total transport.

The complexity of processes at work in the field and in large-scale wave flume experiments makes it difficult to isolate and quantify fundamental processes and to provide measurements of the kind needed for the development of swash numerical models. An alternative to wave flumes for laboratory swash experiments is to generate swash via a dambreak, whereby a reservoir of water is suddenly released in a flume, leading to a bore that collapses on a beach located downstream. The dambreak produces a single, highly repeatable, large-scale swash event, with bore depth, bore speed and maximum run-up comparable to that seen in the field under energetic wave conditions. The set-up avoids many of the complexities associated with swash in the field, and indeed with wave-generated swash in laboratory wave flumes, such as the variability in swash events, swash–swash interactions and the effects of low-frequency oscillations. This reduction in complexity, combined with the ability to repeat the same swash event many times, allows particular fundamental swash processes to be isolated and studied in detail. Moreover, dambreak swash experiments provide good benchmark data for numerical models since the boundary and initial conditions are well defined and data are available with high resolution in time and space. Barnes et al. (2009) used a dambreak set-up to directly measure intra-swash bed shear stress using a shear plate; a similar set-up was used by O'Donoghue et al. (2010) and Kikkert et al. (2012) to study the detailed hydrodynamics of swash over immobile, impermeable beaches of varying surface roughness, and by Kikkert et al. (2013) and Steenhauer et al. (2011) to measure hydrodynamics over and within immobile, permeable beaches. The present study uses the same dambreak facility as used for these previous experiments, but with the beach now consisting of mobile sediment, the primary objective being to measure the intra-swash sediment flux for well-controlled swash conditions. Previous dambreak swash experiments involving a mobile sediment beach are limited to Othman et al. (2014), who used a sloping dambreak apparatus to measure swash uprush sediment transport at the end of a truncated slope, their particular focus being on the influence of grain size and pressure gradient on sediment transport, not on the detailed intra-swash sediment flux.

This paper reports on dambreak swash experiments in which intra-swash flow depth, flow velocity and sediment flux are measured at a number of cross-shore locations for swash on beaches consisting of mobile, coarse-grained sediment. The experiments involve two beach types: a coarse sand beach and a gravel beach. The experimental setup is the same as that used for the permeable, immobile beach experiments of Kikkert et al. (2013), which means that for each of the present mobile bed experiments, the incident bore, beach slope, beach material and beach permeability are the same as for the corresponding immobile beach experiment reported by Kikkert et al. (2013). Comparing hydrodynamic measurements from the present experiments with the hydrodynamic measurements from Kikkert et al. (2013) therefore enables the effects of bed mobility on the swash hydrodynamics to be isolated and quantified. More importantly, the present experiments yield measurements of intra-swash sediment flux for well-controlled, large-scale swash events. To the authors' knowledge, intra-swash flux measurements of this kind, combined with detailed depth and velocity measurements, have not been reported previously.

The details of the experimental setup are presented in Section 2. Section 3 presents the experimental results for shoreline motion, swash depths and depth-averaged velocities, including comparisons with results from the corresponding immobile bed experiments of Kikkert et al. (2012, 2013) in order to quantify the effects of bed mobility on the swash hydrodynamics. The measured intra-swash sediment flux is presented in Section 4, followed in Section 5 by a comparison of the measured flux with the flux calculated using a bed load sediment transport formula. Section 6 concludes the paper with a summary of the main results.

2. Experimental set-up and measurements

2.1. Set-up and test conditions

The experiments were carried out using the same facility used by Kikkert et al. (2012, 2013). A reservoir was placed at one end of a 20 m-long, 0.9 m-high and 0.45 m-wide, glass-sided flume (Fig. 1). The reservoir is fronted by a gate, which is rapidly lifted by a falling-weight mechanism to produce a dambreak-generated bore. The reservoir is 0.983 m long (inside dimension), 0.394 m wide and filled with water to a depth of 0.600 m; the water depth in front of the gate was set at 62 mm. A 1:10 beach was located downstream from the reservoir. The initial shoreline on the beach, corresponding to the intersection of the water surface with the top of the beach roughness, was 0.623 m from the toe of the beach and 4.82 m from the gate. The origin of the $x-z$ coordinate system is at the initial shoreline, with the x-axis parallel to the beach slope and positive shoreward, and the z-axis perpendicular to the slope. The gate is raised at time $t = 0$, resulting in a plunging wave, which produces a bore, approximately 0.25 m high propagating with approximate speed 2.0 m/s towards the beach. The bore collapses on the beach, producing a single, repeatable swash event, with velocity, depth and maximum run-up magnitudes similar to those of full-scale swash in the field.

Experiments were carried out on two beach types: a coarse sand (CS) beach with $d_{50} = 1.3$ mm and a gravel (GV) beach with $d_{50} = 8.4$ mm. Constant head permeameter tests (Steenhauer et al., 2011) established Forcheimer coefficients $a_k = 81.2$ s/m, $b_k = 3587$ s^2/m^2 for the CS beach and $a_k = 4.1$ s/m, $b_k = 383$ s^2/m^2 for the GV beach (here $I = a_k u_D + b_k u_D^2$, where I is hydraulic gradient and u_D is Darcy velocity); the sand is therefore an order of magnitude less permeable than the gravel. The sediments are the same as those used for the corresponding immobile, permeable beach experiments reported in Kikkert et al. (2013), for which the top layer of the sediment beach was made immobile using a dilute cement mix, without changing the permeability (Steenhauer et al., 2011). The permeability of each of the present CS and GV mobile beaches is therefore equal to the permeability of each of the corresponding immobile, permeable beaches reported in Kikkert et al. (2013).

The sediment occupied the full beach, i.e. from the surface of the 1:10 beach face to the floor of the flume. Lines corresponding to the required 1:10 beach slope were drawn on the glass sides of the flume and the beach surface was matched to these lines before each swash run. The 1:10 lines on the glass were approximately 1 mm thick. Between runs the sediment bed was re-shaped by hand so that the top surface