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Experimental study of bore-driven swash hydrodynamics on permeable rough slopes ☆

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ABSTRACT

A detailed experimental investigation of the hydrodynamics of large-scale, bore-driven swash on steep permeable, rough beaches is described. The experiments were carried out on two permeable, but fixed rough beaches, made of 1.3 mm sand and 8.4 mm gravel, respectively. The large-scale discrete swash event was produced by the collapse of a dam break-generated bore on the beach. Simultaneous depths and velocities were measured using laser-induced fluorescence (LIF), and particle image velocimetry (PIV), respectively. Depth time series, instantaneous velocity profiles, depth-averaged velocities, instantaneous turbulent kinetic energy profiles, depth-averaged turbulent kinetic energy, turbulent shear stress profiles and bed shear stresses are presented for several cross-shore measurement locations in the swash. The effect of beach permeability is investigated by comparing new experimental results with previously published data for impermeable beaches with identical surface roughness (Kikkert et al., 2012). The detailed data can be used to test and develop advanced numerical models for bore-driven swash on rough permeable beaches.

1. Introduction

The swash zone is considered to be the most dynamic region of the beach and considerable research effort has been devoted to studying it. The majority of field studies have investigated the swash zone on sandy beaches focusing on the hydrodynamics (e.g., Baldock and Hughes, 2006; Conley and Griffin, 2004; Hughes, 1992; Raubenheimer, 2002) or the sediment transport (e.g., Blenkinsopp et al., 2011; Horn and Mason, 1994; Hughes et al., 1997; Masselink and Hughes, 1998; Masselink and Russell, 2006; Puleo et al., 2000). Field studies on gravel beaches include Austin and Masselink (2006) and Masselink et al. (2010). The field-based investigations have resulted in a reasonable understanding of the main characteristics of the swash zone processes (Butt and Russell, 2000; Elfrink and Baldock, 2002; Masselink and Puleo, 2006). However, more detailed research is required in order to fully understand the key fundamental processes governing hydrodynamics and sediment transport in the swash zone. One of the key processes is the infiltration of water into the beach.

Detailed data sets are usually collected in laboratory experiments, because research carried out in the laboratory enables greater control over the beach conditions. The majority of laboratory studies reported in the literature involve impermeable immobile beds (e.g., Barnes et al., 2009; Kikkert et al., 2012; Petti and Longo, 2001; Shin and Cox, 2006). Lara et al. (2006) created a permeable, fixed bed using wire boxes filled with gravel (nominal diameter of 19 mm or 39 mm) to study the effect of permeability on the hydrodynamics, but the focus of their measurements was on the surf zone, not the swash zone. Other measurements on permeable beaches usually involve mobile sediment (e.g., Pedrozo-Acuña et al., 2006) so that the effects of permeability cannot be separated from the effects of sediment mobility. To the authors' best knowledge no investigations have been carried out on permeable fixed beaches, and focussed solely on the effects of beach permeability on swash hydrodynamics.

The present paper reports new experiments designed to study the detailed hydrodynamics of large-scale bore-driven swash on steep permeable beaches. Experiments were performed on two relatively coarse-grained beaches with different permeability and surface roughness. A detailed description of the subsurface processes recorded in these experiments is reported in Steenhauer et al. (2011). The effect of permeability is investigated by a comparison of the new results with the previously reported results of Kikkert et al. (2012) obtained on impermeable slopes with identical surface roughness and slope.

The paper is organised as follows. Section 2 describes the experimental set-up and measurement. Section 3 presents the experimental results: volume balance for the whole beach, shoreline position, flow depth, depth-averaged velocity and velocity profiles are presented first, followed by results for turbulent kinetic energy, Reynolds stress, bed shear stress and friction factors. The main conclusions of the study are presented in Section 4.

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2. Experimental setup

The experimental setup used to carry out the permeable bed experiments is very similar to the setup used for the impermeable bed experiments of Kikkert et al. (2012). This section therefore highlights only the additional elements of the setup required for the permeable beach experiments.

2.1. Facility

The experiments were carried out in the Fluid Mechanics Laboratory at the University of Aberdeen. A water reservoir was placed inside an existing 20 m long, 0.9 m high and 0.45 m wide wave flume (Fig. 1). The reservoir was fronted by a gate that was raised at high speed (~4 m/s). The initial water depth in the reservoir (h_d) was 600 mm and the initial water depth in front of the beach (h_0) was 62 mm (Fig. 1). With ratio h_d / h_0 of approximately 0.1, raising the gate generated a plunging breaker (Stansby et al., 1998) leading to a bore approximately 0.25 m high with velocity in the order of 2.0 m/s. The bore propagated towards the 1:10 sloped beach located approximately 4.2 m downstream. The beach consisted of sediment throughout its depth. The initial ground water level within the beach was also h_0. This level was controlled by a weir placed 0.5 m beyond the end of the beach.

Experiments were carried out with two different sediments, coarse sand and gravel, with nominal sediment size 1.3 mm and 8.4 mm respectively. Steenhauer et al. (2011) reported the Forchheimer coefficients for both sediments, which show that the gravel is more permeable than the sand by an order of magnitude. The effect of packing on the homogeneity of the sand was minimised by compacting the sediment in the flume under water. A perforated plate at the end of the beach (10.8 m from gate) stopped the sediment from collapsing but still allowed an unobstructed flow of water out of the beach. To create an immobile beach the top 30 mm of the beach was cemented using a dilute water–cement mixture (3% cement by weight, Steenhauer et al., 2011). Separate tests confirmed that, up to the range of the experimental error, the permeability of the sediments was not changed by cementing (Steenhauer et al., 2011). The final beach level was within 1–2 mm of the desired 1:10 slope.

2.2. Instrumentation, measurements and analysis

The origin of the $x - z$ coordinate system is at the intersection between the initial water level and the top of the roughness elements of the beach (Fig. 1). This point is referred to as the initial shore-line location and is 0.623 m from the toe of the beach and 4.82 m from the gate. The x-axis is parallel to the beach slope and positive shoreward, while the z-axis is perpendicular to the slope. The moment that the gate of the reservoir is raised is defined as $t = 0$. Simultaneous velocity and depth measurements were recorded, centred on 6 cross-shore locations at $x =$ -1.802 m, 0.072 m, 0.772 m, 1.567 m, 2.377 m and 3.177 m for the sand beach. For the gravel beach the swash excursion did not reach $x = 3.177$ m, so no measurements were recorded at this location.

Velocities were measured using cross-correlation particle image velocimetry (PIV) and flow depths were measured using laser induced fluorescence (LIF) (Sue et al., 2006). Neutrally buoyant particles (titanium-coated hollow glass particles with a mean diameter of 20 μm) and fluorescent dye with a concentration of approximately 0.1 mg/l were added to the flow and illuminated using a New Wave Solo III Nd YAG Laser. The laser sheet was introduced to the centre of the flow from below the flume, through highly polished 20 mm thick Perspex PIV towers that extended from the bottom of the flume to the beach face. The reflected laser light from the particles and the emitted light from the fluorescent dye were captured by two digital video cameras that were rotated to be aligned with the 1:10 slope of the beach. The PIV camera was rotated slightly backwards to eliminate interference by the free surface when flow depths were small while the LIF camera was rotated forwards so that the camera view was at all times above the free surface. The PIV and LIF systems were combined into a single PIV–LIF system controlled and synchronised by Dantec Dynamics Studio v1.45 software, enabling the velocity and flow depth to be recorded simultaneously at 13.5 Hz. The system was triggered at the moment when the gate was raised. The instantaneous velocity vector fields had a spatial resolution between 1 and 2.5 mm and a random error of 5 to 15 mm/s. The flow depth had an error of approximately 1 pixel, giving instantaneous depth data with a spatial resolution and random error of 0.1 to 0.3 mm.

In addition to the combined PIV–LIF measurements at the 6 locations, a second set of LIF-only measurements was carried out to measure the swash lens, i.e., the instantaneous surface water profile over the whole of the swash extent. For these measurements the Laser was positioned above the flume and illuminated approximately 300 mm of the cross-shore extent of the lens. The complete lens was measured by combining measurements from approximately 12 cross-shore locations (the exact number depended on the maximum run-up).

Repeatability of swash events using the rig was excellent (Kikkert et al., 2012), which meant that measurements from many repeats of the same event could be used to obtain representative ensemble-averages and turbulence measurements. To ensure identical conditions for all repeated runs, water that infiltrated into the beach in the previous run was allowed to drain from the beach. The time required to recover the initial groundwater level was determined by recording the change in water level in the saturated area of the beach prior, during and after a single swash run (Steenhauer et al., 2011). The recovery period for the sand and gravel beach was 60 min and 6 min respectively. Due to the relatively long recovery time, fewer repeats of individual swash events were carried out for the sand beach than for the gravel beach. For the simultaneous PIV/LIF depth and velocity measurements, swash events were repeated 50 times for the gravel beach and 15 times for the sand beach. For the LIF-only measurements of swash depth, experiments were repeated 10 times for the gravel beach and 8 times for the sand beach.

3. Experimental results and discussion

3.1. Surface/subsurface exchange across beach surface

Steenhauer et al. (2011) provide a detailed description of the processes occurring within a permeable beach while the bore climbs its surface. Water infiltrates into the initially unsaturated beach and forms a wetting front, which travels towards the groundwater level.

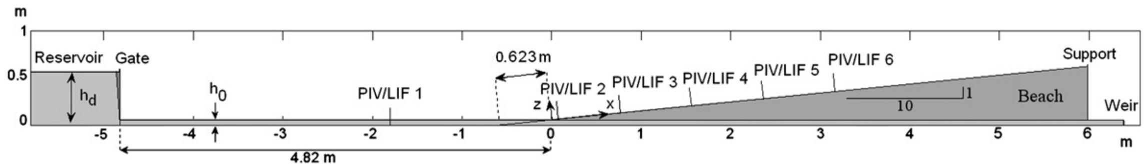

Fig. 1. Permeable bed set-up, initial conditions and PIV/LIF locations.