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Experimental study of bore-driven swash–swash interactions on an impermeable rough slope

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ABSTRACT

Experimental measurements are obtained to investigate the detailed hydrodynamics of wave–wave interactions in the swash-zone. Two bores are generated using a double dam-break mechanism and interact on a 1:10 impermeable rough slope. Measurements of the hydrodynamics are obtained via acoustic displacement sensors and a combined particle image velocimetry and laser induced fluorescent system. Two types of interactions are investigated: wave capture, with the second bore reaching the first one during the uprush, and weak wave–backwash interactions when interaction happens during the backwash of the first wave. The relative strength of the bores at the initial shoreline and time between their arrivals determines the initial type of interaction, however the type as well as the intensity of the interaction may vary throughout the swash-zone for the same swash event. During wave capture and weak wave–backwash interactions, the fluid of the first bore is advected upwards, then mixed with the fluid of the second bore by intense shearing and highly turbulent vortices generated at the front of the second bore because of the relative velocity differences between the two bores. The details of the hydrodynamics during interaction confirm the potential of swash–swash interactions to suspend sediment and transport it shoreward or interrupt seaward sediment transport.

1. Introduction

The flow in the swash zone is characterised by a high uprush velocity, a direction-reversal and a high backwash velocity while it is also highly turbulent, unsteady and non-uniform. On a mobile bed, this results in large sediment transport fluxes and hence the swash zone plays an important role in the dynamics of the foreshore and the constant evolution of the beach profiles. Many studies have investigated the detailed hydrodynamics of the flow in the swash zone (e.g. Barnes et al., 2009; Cowen et al., 2003; Kikkert et al., 2012, 2013; O'Donoghue et al., 2010; Petti and Longo, 2001), however these have focused on a single incoming bore climbing an initially dry beach. In comparison, there are relatively few investigations that focus on the interaction by successive swash events, despite field observations suggesting that the impact of the interactions on the sediment transport may be considerable (e.g. Hughes and Moseley, 2007; Masselink et al., 2009).

Swash–swash interaction occurs when the period of the incident wave is smaller than the period of the swash event. The downshift in frequency between the incident wave and the swash is caused by uprush–backwash interactions when bores arriving at the initial shoreline are strong, and by standing long-waves in the swash-zone when bores arriving are weak (Mase, 1995). The degree of swash–swash interaction depends on beach slope, incident wave period and its height (Brocchini and Baldock, 2008). Swash–swash interactions do not occur along the full extent of the swash zone. Hughes and Moseley (2007) defined the region where interactions occur as the outer swash-zone. In the inner swash-zone, which is further landward, no interactions occur and the flow is a pure swash motion. Mase and Iwagaki (1985) defined two different types of interactions. The first occurs during the uprush of the first bore and hence the second bore overtakes the first bore. This is referred to as wave–capture interaction. The second type occurs during the backwash of the first bore, either before or after the backwash flow has become supercritical and formed a backwash bore (Hibberd and Peregrine, 1979). Propagation of the second bore is suppressed by the first bore, and this is referred to as wave–backwash interaction. A further distinction was made by Hughes and Moseley (2007) and Cáceres and Alsina (2012). For a weak wave–backwash interaction, the receding backwash has a limited amount of energy and the overrun of the incoming uprush results in an onshore flow. For a strong wave–backwash interaction, the backwash is stronger than the incoming uprush, therefore the resulting flow is offshore directed.

The importance of swash–swash interactions was recognised by Kemp (1975) who qualitatively related the interactions to the sediment transport by suggesting that swash collisions may indicate whether a beach erodes or accretes. Swash–swash interactions also transfer wave momentum to longshore flows (Brocchini, 1997; Brocchini and

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Peregrine, 1996; Ryrie, 1983). Mase and Iwagaki (1985) found that the ratio of the number of run-up events to the number of incoming waves decreases with decreasing slope and increasing deep-water wave steepness and hence the number of interactions increased. Field measurements by Weir et al. (2006) found good correlation between the boundary of erosion and accretion in the swash zone and the landward limit of swash interactions. Field measurements by Holland and Puleo (2001) indicated that if no interactions occur, because the swash duration is shorter than the period of the incoming wave, entrained sediments are deposited outside of the swash zone therefore flattening the beach. However, this also increases the swash duration until eventually the swash duration is equal to the period of the incoming waves and the rate of change of the profile becomes zero. If interactions do occur, the sediments are deposited in the swash zone, steepening the beach and thereby decreasing the duration of the swash event. This is in agreement with the results from Alsina et al. (2012), who compared experimental data from a steep beach with those from an artificially flattened beach. On the flattened beach, the swash period increased and hence the number of interactions increased. As a result the strength of the backwash was reduced and this reduced the offshore sediment transport. Alsina and Cáceres (2011) and Cáceres and Alsina (2012) found that all swash–swash interaction types induce high concentrations of suspended sediments. The strong wave–backwash interaction induces the highest concentration which is generally directed offshore. Sediments suspended by weak wave–backwash interaction, which occurs most frequently, and wave–capture interaction are generally directed onshore. Erikson et al. (2005) included the effects of swash–swash interactions into their model that predicts shoreline motions and found that the predictions matched laboratory measurements obtained on gentle beaches significantly better than when the interactions were not included in the model, but on steep beaches there was little improvement. This matched results by Hughes and Baldock (2004) whose model did not take into account the effects of interactions, but predictions on steep beaches, where swash interactions did occur, nevertheless provided a reasonable match with field measurements.

Detailed measurements of the fundamental kinematics of swash–swash interactions, that cause the suspension of sediments, are rare. Barnes and Baldock (2007) carried out laboratory experiments to obtain measurements of flow depth, velocity and bed shear stress of wave–backwash interaction, but used a simplified set-up generating a quasi-steady hydraulic jump. Field studies (e.g. Masselink et al., 2009) and large scale laboratory studies (e.g. Alsina and Cáceres, 2011) that included measurements of flow depth and velocity of interacting swash events focused on the overall swash processes that generate beach erosion or accretion, not on the specific kinematic details of the interactions.

Numerical models based on the non-linear shallow water (NLSW) equations have been used to simulate the behaviour of incoming wave groups in the nearshore zone, and therefore include interactions in the swash-zone (e.g. Orszaghova et al., 2014; Watson and Peregrine, 1992; Watson et al., 1995). However the focus of these studies was predominantly the surf-zone. In addition, experimental data used to validate these model predictions was also obtained predominantly in the surf-zone and hence the accuracy of the predictions in the swash-zone is still unknown.

This knowledge gap and lack of data have motivated the present investigation which aims to increase our fundamental understanding of swash–swash interactions and to create a data set suitable for testing of numerical models of swash–swash interactions in the swash zone. A new series of experiments has been carried out in the laboratory on a rough impermeable slope. The bore-driven swash is generated through the use of a dam-break mechanism (e.g. Kikkert et al., 2012; O'Donoghue et al., 2010). A second reservoir is added to enable a second bore to be generated with a pre-determined time lag. A range of swash–swash interactions is generated by varying the relative water levels in the two reservoirs and the time lag between bores. Flow depth measurements from acoustic displacement sensors are used to study the general behaviour of swash–swash interactions. For two specific cases, a wave–capture and weak wave–backwash interaction, simultaneous measurements of the flow depth (using laser induced fluorescence) and velocity (using particle image velocimetry) are obtained. Analysis of the ensemble averaged quantities and turbulence is used to study the hydrodynamics of the swash–swash interactions in detail.

2. Methodology

2.1. Experimental set-up

The experiments were carried out in the 12.5 m long, 0.45 m high and 0.30 m wide glass-sided Armfield SII flume located in the Water Resources Laboratory of the Hong Kong University of the Science and Technology. Swash–swash interactions of similar scale as found in the field were generated in the laboratory by a double dam-break system positioned at one end of the flume (Fig. 1). The system consisted of a reservoir, two gate mechanisms and an aluminium support framework. The reservoir, made from Perspex, had an internal width of 0.279 m,

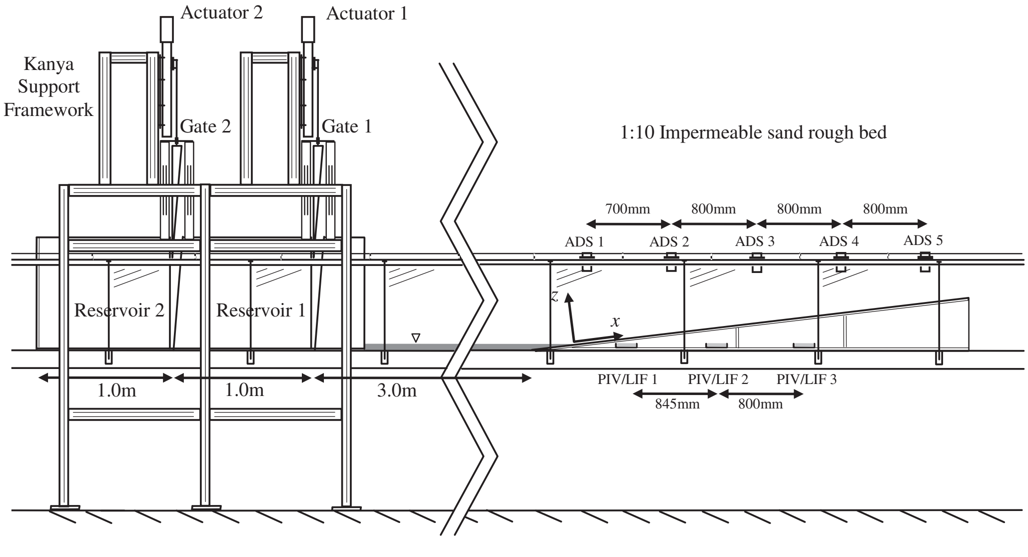

Fig. 1. Experimental set-up of double dam-break system and impermeable rough bed with locations of ADS and PIV/LIF measurements.