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An experimental study of the interaction of two successive solitary waves in the swash: A strongly interacting case and a weakly interacting case

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ABSTRACT

The interaction of successive solitary waves in the swash zone have been studied using large-scale experiments with a simple bathymetry of a constant depth region, where the water depth was 1.72 m, and a plane beach, whose slope was 1:12. Two wave cases were considered where two successive solitary waves of the same height were generated one after the other so that the wave crests were separated by the effective wavelength associated with a single solitary wave. In the weakly interacting case, the swash period associated with a single solitary wave is smaller than the time period separating the successive wave crests, which leads to similar run-ups for the first and second wave, whereas in the strongly interacting case, the swash period associated with a single solitary wave is larger than the time period separating the successive wave crests, which leads to a significant reduction in the run-up of the second wave. The degree to which there is an interaction between the swash uprush of the second wave and the downrush of the first wave is found to be related to the solitary wave slope parameter, which predicts breaker type of the first wave. Previous data from literature are found to support this claim. Measurements of bed shear stress, bed pressure, and the free-surface displacement at a location near the stillwater shoreline are used to describe how the dynamics of the boundary layer differ when the downrush of the first wave meets the incoming second wave in both cases.

1. Introduction

The swash zone is the subregion of the nearshore region that is periodically covered and uncovered by a flow of water due to wave action. It is recognized as an important dynamic zone for sediment transport and beach morphological changes (see Masselink and Puleo, 2006; and reviews by Elfrink and Baldock, 2002; Brocchini and Baldock, 2008; Bakhtyar et al., 2009). The typical swash flow is characterized by shallow flow depths (Meyer and Taylor, 1972), bore- and bed-generated turbulence (Cowen et al., 2003; Longo et al., 2002; Sou et al., 2010), and cross-shore flow accelerations (Baldock and Hughes, 2006; Shen and Meyer, 1963).

To study an isolated swash event, laboratory studies frequently use a dam-break-generated bore to drive the swash on impermeable beds (*e.g.*, Barnes et al., 2009; Kikkert et al., 2012; O'Donoghue et al., 2010; Yeh et al., 1989) and permeable beds (*e.g.*, Kikkert et al., 2013; Othman et al., 2014; Postacchini et al., 2014), motivated by the close resemblance between a long wave that breaks in the surf zone before traveling as a fully developed bore toward the shoreline and a dam-break-generated bore. Solitary waves have also been used to study isolated swash events, motivated by questions of tsunami run-up (reviews by Synolakis and Bernard, 2006; Madsen et al., 2008) and motivated by observations that long waves on a beach often resemble a train of solitary waves (Peregrine, 1983). Experimental studies of solitary waves approaching a beach include measurements of run-up (Jensen et al., 2003; Li and Raichlen, 2002; Pedersen et al., 2013), flow turbulence (Ting, 2006, 2008), and sediment transport (Alsina et al., 2009; Kobayashi and Lawrence, 2004; Sumer et al., 2011). A previous study by the authors (Pujara et al., 2015, henceforth referred to as PLY15) also examined the swash event driven by solitary waves on a plane beach to investigate the effects of wave breaking on the flow evolution, bed shear stress, and run-up in the swash.

The swash on natural beaches is often characterized by the arrival of multiple waves causing successive swash events that may interact with each other. These swash–swash interactions have been identified as an important feature for sediment transport (Hughes and Moseley, 2007; Puleo and Butt, 2006), run-up (Erikson et al., 2005; Lo et al., 2013), and the generation of low-frequency waves (Brocchini and Baldock, 2008; Watson et al., 1994). Alsina et al. (2012) and Cáceres and Alsina (2012) have shown the importance of swash–swash interactions by using a wave-by-wave analysis of laboratory data—such interactions suspend significant amounts of sediment into the water column that can then be advected long distances in the cross-shore direction. On

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the other hand, Peregrine (1966) and, more recently, El et al. (2012) have shown that the evolution of an undular bore on a flat bottom and a gently sloping bottom leads to a system of multi-crested waves whose asymptotic forms are solitary waves. Wiegel (1990) and Galvin (1990) showed a limited amount of field evidence for this process, known as soliton fission, in the case of the transformation of a long ocean swell over a reef. Thus, the interacting swash events of successive solitary waves arriving at a shoreline not only offers a convenient way to isolate swash–swash interactions, but may also be a common feature on natural beaches.

The aim of this study is to examine the swash of successive solitary waves using large-scale experiments with detailed measurements of the boundary layer, including direct measurements of bed shear stress using a shear plate sensor. Two specialized cases of two successive solitary waves, where wave crests are separated by the effective wave period of a single solitary wave, are generated to study two qualitatively different types of swash–swash interactions. The paper is organized as follows. The laboratory setup is described in Section 2, including descriptions of the shear plate sensor and generation of successive solitary waves. Section 3 presents the results for the two wave cases. Section 4 discusses the results in the context of run-up of successive solitary waves and provides the conclusions.

2. Laboratory experiments

2.1. Experimental setup

The experiments were conducted in the Large Wave Flume (LWF) at the Hinsdale Wave Research Laboratory at Oregon State University. The LWF, which was a flume of length 104 m, width 3.7 m, and depth 4.6 m equipped with a piston-type wavemaker at one end of the flume and a plane beach of slope $s = 1/12$ installed at the other end, is shown as a schematic in Fig. 1. In between the wavemaker and the toe of the beach, the flume bottom was horizontal and the water depth was kept constant at $h_0 = 1.72$ m. The incident waves were measured at the offshore location 21.4 m from the wavemaker in its fully retracted position. The free-surface displacement was measured using a resistance-type wave gage (custom designed for the LWF; estimated repeatability <2 mm), the water particle velocity was measured using an acoustic Doppler velocimeter (ADV; Nortek Vectrino with plus firmware, accuracy 1%) installed at a depth of 1.1 m below the stillwater free-surface. Further measurements of the free-surface displacement and water particle velocity were also made at a location near the toe of the beach (the near-toe location shown in Fig. 1) using a resistance-type wave gage and an ADV installed at a depth of 0.8 m below the stillwater free-surface.

To allow the study of the interaction between the downrush of the first wave and the uprush of the second wave, additional measurements were made at the nearshore location shown in Fig. 1, which was located at $x = -1.21$ m and where the local stillwater depth was $h = 0.10$ m. The local bed shear stress was measured using a shear plate sensor (more details below), the free-surface displacement was measured using an ultrasonic wave gage (Senix TS-30S1 series; accuracy 1 mm) mounted directly above the center of the shear plate sensor, the bed pressure was measured using a pressure transducer (Druck PDCR 830; accuracy 30 Pa) installed so that its measurement face was flush with the bed, and the near-bed velocity was measured using a side-looking ADV (Nortek Vectrino with plus firmware) mounted with its measurement volume at a height of 2 cm above the bed. When the water depth was less than approximately 7 cm, the near-bed velocity measurements were not available because the ADV failed to make reliable measurements. A minimum threshold of 15 dB for the signal-to-noise ratio (SNR) was applied to the ADV measurements. All instruments at the nearshore location were co-located in the cross-shore direction, but the bed pressure sensor and the ADV were offset in the long-shore direction from the shear plate sensor. A photograph of the top view of the instrument setup is shown in Fig. 2.

The shear plate sensor, shown schematically in Fig. 3, was specifically designed to measure the local bed shear stress in the swash zone. A full description of the shear plate sensor is given in Pujara and Liu (2014), but a brief overview is provided here. The shear plate has dimensions of length 43 mm (cross-shore) and width 136 mm (long-shore) and thickness 0.8 mm. The displacement of the shear plate due to the force of fluid friction on its surface area is measured by an eddy-current proximity probe; the probe uses the interaction between applied magnetic fields and induced eddy-currents to gage the distance from the probe face to the target plate (labeled in Fig. 3). The displacement of the shear plate is resisted by cylindrical links of known stiffness attached to the shear plate on its underside. The links maintain a right angle with the shear plate and the base plate, acting as a clamped guided cantilever system. A small gap of 1 mm surrounds the perimeter of the shear plate to allow for deflections. The shear plate sensor has a range of ± 200 Pa and an accuracy of ± 1%, making it suitable for accurately measuring the large bed shear stresses in the swash zone. In the presence of streamwise pressure gradients, there exists a secondary force on the shear plate, but this is corrected for using the method in Pujara and Liu (2014). The principal advantage of the shear plate sensor is its ability to make direct measurements of bed shear stress throughout the swash cycle without assumptions of the structure of the boundary layer flow.

Apart from the measurements in the swash, the shoreline motion was also tracked using two overhead cameras (Panasonic AW-HE60), which yielded images with a resolution of 1 cm/pixel after processed to remove perspective. A tracking algorithm, which looked for large optical gradients, was used to track the shoreline during the uprush phase. It was not possible, however, to track the shoreline position during the downrush phase since it did not create an indentifiable optical signature.

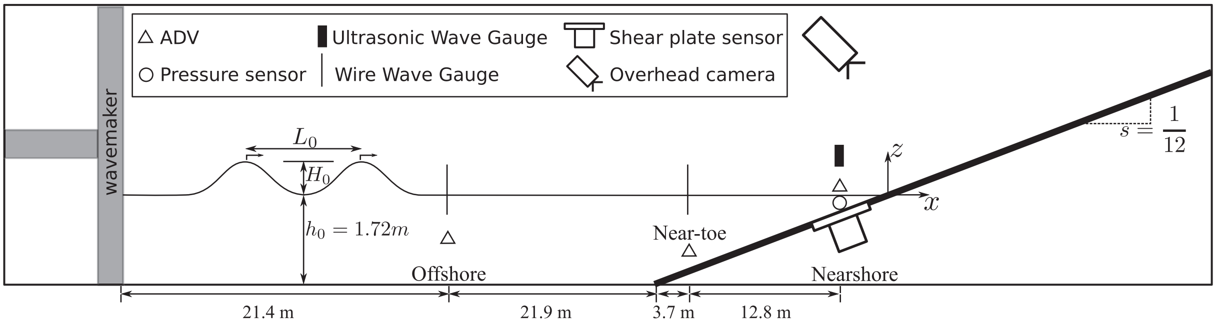

Fig. 1. Schematic of experimental setup. H_0 is the solitary wave amplitude, h_0 is the stillwater depth in the constant depth region, L_0 is the separation distance between wave crests of successive solitary waves and is designed to be the same as the effective wavelength associated with a single solitary wave in these experiments. The local stillwater depths at the near-toe location and nearshore location were $h = 1.42$ m and $h = 0.1$ m, respectively.