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Vertical structure of near-bed cross-shore flow velocities in the swash zone of a dissipative beach

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ABSTRACT

Cross-shore velocity profiles are measured at 0.001 m vertical resolution and at 100 Hz over the lower 0.02–0.07 m of the water column in the mid swash zone on a dissipative, macrotidal beach. Swash motion is predominantly at infragravity frequencies and forced by significant wave heights exceeding 1.5 m and peak wave periods over 15 s. Observations of long duration (> 14 s) swashes during two rising tides are used to quantify the vertical structure of cross-shore flow velocities and estimate corresponding bed shear stress and friction coefficients. Analysis is performed on an individual swash event to an elevation of 0.07 m and an ensemble event made up of 24 individual swash events to an elevation of 0.02 m. Cross-shore velocities exceed 2 m s^{-1} and are of a similar magnitude during both the uprush and the backwash. Changes in velocity with elevation indicate that the swash zone boundary layer extends to 0.07 m during the strongest flows and is well-represented by the logarithmic model applied to this elevation, except near flow reversal. Maximum bed shear stresses estimated using the logarithmic model are 22 N m^{-2} and 10 N m^{-2} for the individual event and ensemble event respectively and mean values are larger during the backwash than the uprush. Mean friction coefficients estimated from equating the logarithmic model and the quadratic drag law are 0.018 and 0.019 for the individual event and ensemble event respectively. Bed shear stress may be underestimated if the logarithmic model is fit to a velocity profile that is only part boundary layer, emphasising the need for high resolution velocity profiles close to the bed for accurate bed shear stress predictions in the swash zone.

1. Introduction

The swash zone is commonly defined as that part of the beach that is alternately covered and exposed by uprush and backwash (Elfrink and Baldock, 2002; Masselink and Puleo, 2006). Large flow velocities in shallow depth, high turbulence levels and large sediment transport rates make the swash zone arguably the most dynamic part of the nearshore region (Masselink et al., 2005; Masselink and Puleo, 2006). These characteristics create sediment transport gradients which drive rapid morphological change on the beachface. Hence, a detailed understanding of swash zone processes is vital in the modelling of shoreline evolution. The understanding of swash zone processes has progressed considerably over the last decade or so as more specialized sensors have made it easier for coastal scientists to collect data from this notoriously challenging environment. This progress has been documented in a number of review papers (Butt and Russell, 2000; Elfrink and Baldock, 2002; Masselink and Puleo, 2006; Brocchini and Baldock, 2008).

Swash events consist of three distinct phases; uprush, flow reversal, and backwash. A variety of methods have been used to measure the flow characteristics during swash events and several patterns have emerged. Uprush flows typically originate by the collapsing surf zone bore and are sometimes accompanied by a brief period of flow acceleration immediately following bore collapse (Nielsen, 2002; Jensen et al., 2003; Puleo et al., 2007). The velocity and landward extent of uprush is controlled by the forcing conditions in the surf zone, beach gradient and sediment characteristics. Maximum velocities approaching 2 m s^{-1} have been recorded on gently sloping beaches (Butt and Russell, 1999; Masselink et al., 2005) and 3 m s^{-1} on steep beaches (Masselink and Hughes, 1998). Flow velocities are onshore-directed during the uprush, but flow in the lower swash zone often reverses before the uprush has reached its maximum landward extent (Masselink and Puleo, 2006). Backwash flows accelerate under the forces of

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gravity and offshore-directed pressure gradients (Baldock et al., 2001). The duration of backwash is typically longer than that of uprush with slightly weaker velocities (Puleo et al., 2003, 2012; Masselink et al., 2005; Aagaard and Hughes, 2006).

Several studies have documented the vertical flow structure of swash in laboratory conditions over fixed, impermeable beds. Many of these have fitted cross-shore velocity profiles to a logarithmic model, commonly known as the Law of Wall, and found excellent agreement ($r^2 > 0.9$) for most of the swash cycle (Cox et al., 2000; Petti and Longo, 2001; Archetti and Brocchini, 2002; O'Donoghue et al., 2010; Kikkert et al., 2012). This agreement is despite the Law of Wall being designed for steady flows with fully developed boundary layers; not accelerating, reversing or stratified flows. However, fewer studies have attempted to quantify the vertical flow structure of swash on a natural foreshore. This is partially due to instrument limitations that typically do not allow for measurements close to the bed (< 0.02 m), or the deployment of multiple sensors at a particular location. In addition, changes in bed level elevation can occur rapidly under active swash (Masselink et al., 2009; Puleo et al., 2014a), hence instrument elevation will vary during a swash event, over a tidal cycle and indeed throughout a field experiment. Raubenheimer et al. (2004) used acoustic Doppler velocimeters (ADV) to obtain velocities at elevations of 0.02, 0.05 and 0.08 m above the bed on a gently sloping beach. The cross-shore velocity profiles were fitted to the logarithmic model and were found to be approximately logarithmic within 0.05 m of the bed. Masselink et al. (2005) recorded the velocity at 0.03 and 0.06 m above the bed using electromagnetic current meters and reported that the thickness of the boundary layer was at least 0.03 m during the start and end of the swash cycle on a low gradient, macrotidal beach. More recently, using a newly developed high resolution acoustic Doppler current profiler, Puleo et al. (2012) measured the cross-shore velocity profile in the lower 0.02 m of the water column at a spatial resolution of 0.001 m on a microtidal, low energy beach. Cross-shore velocities in the lower 0.02 m of the water column were well represented by the logarithmic model ($r^2 > 0.9$), except around the time of flow reversal. Despite being undertaken on a natural beach, the energy level of the forcing conditions during this study is comparable to that observed under laboratory settings with significant wave heights not exceeding 0.16 m and peak wave periods between 4 and 6 s. Instrument limitations have required that past studies assume that the logarithmic boundary layer is at least as large as the elevation of the highest sensor used in applying the logarithmic model. More research is needed to explore how the model applicability is influenced by the number of points used in the velocity profile and the elevation over which the Law of Wall is applied.

A number of previous studies have estimated bed shear stress in the swash zone indirectly using the Law of Wall or the quadratic drag law. A considerable variation of bed shear stress estimates in the swash zone exists in the literature. This variation can be attributed partly to differences in estimation techniques, forcing conditions and the cross-shore location in the swash zone where measurements were taken. A general trend in both laboratory (Archetti and Brocchini, 2002; Cowen et al., 2003; Kikkert et al., 2012) and field studies (Masselink et al., 2005) is for bed shear stress to be larger during uprush than backwash. For example, Masselink et al. (2005) calculated maximum bed shear stresses during the uprush of around 25 N m^{-2} and only 10 N m^{-2} during backwash on a dissipative beach with a significant wave height of 1.5 m. This trend is consistent with direct measurements of bed shear stress made in the laboratory (Barnes et al., 2009) and the field (Conley and Griffin, 2004). Direct measurements of bed shear stress taken by Conley and Griffin (2004) using a flush mounted hot film anemometer were, however, an order of magnitude smaller than those estimated by Masselink et al. (2005). The difference between uprush and backwash shear stress magnitudes is generally attributed to excessive bore-related turbulence during the uprush and, in the field, the thinning of the boundary layer due to infiltration (Conley and Inman, 1994; Petti and Longo, 2001). In contrast to this trend, Puleo et al. (2012) calculated peak bed shear stresses of 4 N m^{-2} during uprush and 7 N m^{-2} during backwash using high resolution velocity profiles measured during low energy conditions. However, due to the use of acoustic sensors in this study, the velocity profile at the beginning of the uprush when bed shear stresses are potentially largest was not measured. Additionally, Puleo et al. (2012) estimated bed shear stress using cross-shore velocities from only two elevations above the bed, analogous to the method used by Masselink et al. (2005). Differences of nearly 100% were reported between the two methods, suggesting that more highly resolved cross-shore velocity profiles are necessary to give an accurate estimate of bed shear stress using the logarithmic model.

The quadratic drag law has been widely used to calculate bed shear stress when velocity profile information is not available. This method is dependant upon a free stream velocity measurement and a friction coefficient which is normally a constant value. Several studies have inferred swash zone friction coefficients by equating the logarithmic model and the quadratic drag law when profile data exist. Results from these studies vary significantly ($0.001 < f < 1$) (Cox et al., 2000; Archetti and Brocchini, 2002; Cowen et al., 2003; Raubenheimer et al., 2004; Barnes et al., 2009; O'Donoghue et al., 2010; Puleo et al., 2012). This variance is due mostly to differences in experimental conditions. In studies where bed shear stress was larger (smaller) during uprush, the mean friction coefficient during uprush was also greater (lesser) (Archetti and Brocchini, 2002; Cowen et al., 2003; Puleo et al., 2012). Friction coefficients estimated at different locations in the swash zone of a laboratory beach were relatively constant across the full width of the swash zone (Barnes et al., 2009). The friction coefficient is heavily influenced by the elevation above the bed at which the velocity used in the quadratic drag law is obtained. This velocity is usually taken from the highest current meter without knowledge of whether or not the velocity is located in the free stream. Puleo et al. (2012) explored the impact of using velocities from different elevations and found that the friction coefficient is considerably larger when velocities close to the bed are used. For example, using the velocity from an elevation of 0.02 m gave a mean friction coefficient of 0.034, whereas the velocity from 0.005 m gave a mean friction coefficient of 0.11.

Past studies have indicated that the logarithmic model may be applicable to swash flow, except during the initial stages of uprush and during flow reversal. However, the model is yet to be fully validated with high resolution velocity profile measurements under high energy conditions on a natural foreshore. Evidence suggests that high resolution velocity profiles close to the bed are necessary for improving confidence in estimating swash zone bed shear stresses and sediment transport rates. This paper reports on high resolution (0.001 m) cross-shore velocity profiles that have been recorded in the swash zone boundary layer of a high energy, dissipative beach. The main objectives of this paper are to: (1) investigate the applicability of the logarithmic model; (2) to identify temporal variability in the thickness of the swash zone boundary layer; and (3) to quantify corresponding bed shear stresses and friction coefficients.