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Direct bed shear measurements under loose bed swash flows

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A B S T R A C T

Shear plate measurements of bed shear stress under fixed and loose bed swash uprush flows are presented and contrasted. A shear plate previously developed for fixed bed flows was modified and tested for coarse and fine grain loose beds. Transient flows were generated by a dam-break flow over initially dry horizontal and sloping beds, with flows upslope analogous to swash uprush flows on beaches. Performance of the shear plate varied with grain size. For the coarse grained loose beds only the peak shear stress at the leading edge of the swash flow was consistently obtained; for fine grained loose beds the shear stress was reliably obtained over the whole uprush swash cycle. Data were obtained for varying thickness of loose bed material, commencing with a single grain layer, which correspond to partially starved bed conditions. The direct measurements clearly indicate that the bed shear stress comprises of a fluid shear stress component and a grain shear stress component. The grain shear stress increases linearly with sediment load and is significantly larger for the coarse loose grain bed tests due to the much larger normal stress compared to that for fine grain loose bed tests with the same number of grain layers. The data show a high degree of consistency with the classical theory of Bagnold (1956) and the derived coefficient of dynamic internal friction is similar to that observed by Hanes and Inman (1985).

1. Introduction

Improved predictions of sediment transport rates in the swash zone rely on accurate estimates of the bed shear stress and are fundamental to enhancing the accuracy of models for beach erosion and accretion. As highlighted recently at the 2nd International swash workshop, significant challenges remain in determining bed shear stress in the swash zone, both under fixed beds and notably for loose beds. Techniques to measure the bed shear stress include estimates based on fitting the log-law to velocity profiles, hot film measurements or direct bed shear measurement via shear plates. While limited hot film measurements exist for the swash zone (e.g. Conley and Griffin, 2004), data-model comparisons from laboratory studies perhaps suggest that direct shear plate measurements are more reliable than log-law estimates (Allis et al., 2014; Torres-Freyermuth et al., 2013). Further, even at field scale or in large scale experiments, obtaining reliable velocity profile measurements at the leading edge of the swash flow is beyond the state of the art, even with PIV or ADVP instrumentation. A comprehensive review of recent measurements is presented by Allis et al., 2014.

Previous laboratory measurements have focused predominantly on smooth beds or fixed beds (Barnes et al., 2009; Pujara and Liu, 2014; Riedel and Kamphuis, 1973; Seelam et al., 2011; You and Yin, 2007). The most recent work for these bed conditions was reported by Torres-Freyermuth et al. (2013) and reaches similar conclusions to Barnes et al. (2009). Limited data exists for loose beds. Rankin and Hires (2000) performed direct measurements of the total force on a thick loose rippled bed under wave motion, where forces are dominated by pressure forces as opposed to shear forces. Conley and Griffin (2004) reported measurements using a hot-film anemometer on a natural beach but with the hot-film plate mounted above the sand surface (their Fig. 4). The data were consistent with smooth plate boundary layer theory, perhaps suggesting that the additional roughness from the sand was not accounted for. Estimates of the flow velocity were also unavailable. Log-law fitting over loose beds in the field (Masselink et al., 2005; Puleo et al., 2012) suggests that stresses are greater in the uprush than in the backwash, consistent with fixed bed data from shear plates and the log-law (Kikkert et al., 2012, 2013; O'Donoghue et al., 2010). However, in the field case, no direct comparison between fixed and loose beds is possible. The classical experiments on dispersive and tangential stress by Bagnold (1954) and his theoretical development of the dynamics of sheared grains (Bagnold, 1956; see also Nielsen, 1992) imply that a grain shear stress component occurs for loose beds, where the bed shear stress, τ, at the level of immobile grains comprises a fluid stress, τ_f, and a grain stress, τ_g,

$$\tau = \tau_f + \tau_g \tag{1}$$

where $\tau_g = \sigma_e \tan \varphi_r$, σ_e is the normal stress and φ_r is the dynamic angle of internal friction, such that τ_g is equivalent to Coulomb sliding friction (Hanes and Inman, 1985). To our knowledge, there are no direct shear stress measurements testing this hypothesis under either wave motion or swash flows. The present paper addresses this issue and presents direct loose bed shear stress measurements in swash flows using the

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shear plate developed and validated by Barnes and Baldock (2007) and later studies (Allis et al., 2014; Barnes et al., 2009; O'Donoghue et al., 2010; Seelam et al., 2011). Shear stress data from fine (d_{50} = 0.22 mm) and coarse (d_{50} = 2.85 mm) loose beds of varying thickness are contrasted with data from smooth and fixed beds, the latter using the same sediment grains. The focus in particular is on the differences in the peak shear stress at the wave front. Transport rates are also determined for the loose bed experiments by sediment trapping, although these correspond to starved bed conditions. The paper is organised as follows. Section 2 outlines the apparatus and instrumentation, together with the hydrodynamic model used to obtain the flow velocity. The hydrodynamic model is validated in Section 3, followed by discussion of the shear stress data in relation to Eq. (1), and the associated friction factors and sediment transport. Final conclusions are given in Section 4.

2. Experimental arrangement

2.1. Apparatus and instrumentation

The experiments were conducted in a dam-break flume, which comprises of a PVC bed with glass walls, and follow the basic methodology of Barnes et al. (2009). Dam-break flows have a very close analogy to swash flow during the uprush phase (Hogg et al., 2011; Peregrine and Williams, 2001; Pritchard et al., 2008). The dimensions of the flume are 3 m long, 0.4 m wide and 0.4 m deep (Fig. 1). The flume can be operated horizontally, or tilted, in this case upward, to represent a sloping beach face during swash uprush. Simultaneous free surface elevations of the dam-break flow were measured by an array of (six) MicroSonic Acoustic Displacement sensors, sampled at 25 Hz. Sensor 1 was installed on the dam gate for the purpose of resolving the time of gate opening. The remaining five sensors (2–6) were deployed along the centre of the flume, spaced at same interval (10 cm). The celerity of the leading edge of the swash front is obtained from the propagation time between sensors (Barnes et al., 2009).

The Swash Shear Plate (SSP, Fig. 2) is based on the shear cell design of Grass et al. (1995) and has been previously used in a number of studies of dam-break swash, bore driven swash (Allis et al., 2014; Barnes, 2009; Barnes and Baldock, 2007; O'Donoghue et al., 2010) and solitary wave (Seelam et al., 2011) bed shear stress. However, these previous studies only considered smooth or fixed impermeable sediment beds. In brief, a lightweight aluminium shear plate (0.1 m long, 0.25 m wide and 0.75 mm thick) is supported by four tubular legs (diameter 1.1 mm) clamped at the bottom of the cell, and which provide the restoring force. The motion of the plate is sensed by an Indikon Eddy Current Proximity Sensor (AP-1264) with a resolution of 0.001 mm. Shear stress and water level sensor data are logged synchronously to computer and post-processed via calibration coefficients to obtain the temporal variation of the bed shear stress and water elevation or depth. The shear plate is calibrated in-situ from static force/displacement curves, which yield a linear relationship with an R^2 value better than 0.99. The ultrasonic sensors provide the water surface elevation either side of the shear plate, from which the pressure gradient force (Froude–Krylov force) is obtained and removed from the total measured force, yielding the skin friction force or shear stress. The volume of grains glued to the plate is included in these calculations as appropriate. The pressure gradient across the plate is obtained from a hydrostatic assumption in the free stream flow and in the cell, following validation of this hypothesis by Barnes et al. (2009). It is noted for these swash flows that the skin friction force is typically an order of magnitude greater than the pressure gradient force and therefore potential errors due to the pressure gradient component of the total force are small compared to those when using the same technique under wave motion (see Grass et al., 1995; Rankin and Hires, 2000 and Pujara and Liu, 2014 for further discussion).

While the application of the SSP for direct shear stress measurements has been well validated for smooth and fixed bed conditions, some further challenges occur for loose bed conditions, notably that sediment may jam in the gap around the shear plate and that scour can occur, exposing the shear plate or casing so that it protrudes into the flow, disturbing the boundary layer in the process. The potential difficulty of scour exposing the casing is negated by keeping the plate mounted flush with the underlying fixed bed and varying the thickness of the sediment layer above the plate. If sediment particles jam in the gap (approximately 1 mm) between the shear plate and cell casing then the shear plate may not respond fully to the initial swash flow at the leading edge, nor be able to restore correctly toward the original position after the swash front passes and the stress decreases. For fine grains, sediment may also settle through the gap, entering the shear cell. Relatively quickly, cumulative sediment build up occurs, filling the cell sufficiently to impact on the resistance provided by the tubular legs.

A number of options were considered and tested to counter these issues. Initially, a sheet of latex rubber was glued to the shear plate and casing, fully sealing the gaps. However, the movement of the shear plate was restricted at the corners of the cell and consistent calibration and data could not be obtained. Subsequently, this arrangement was

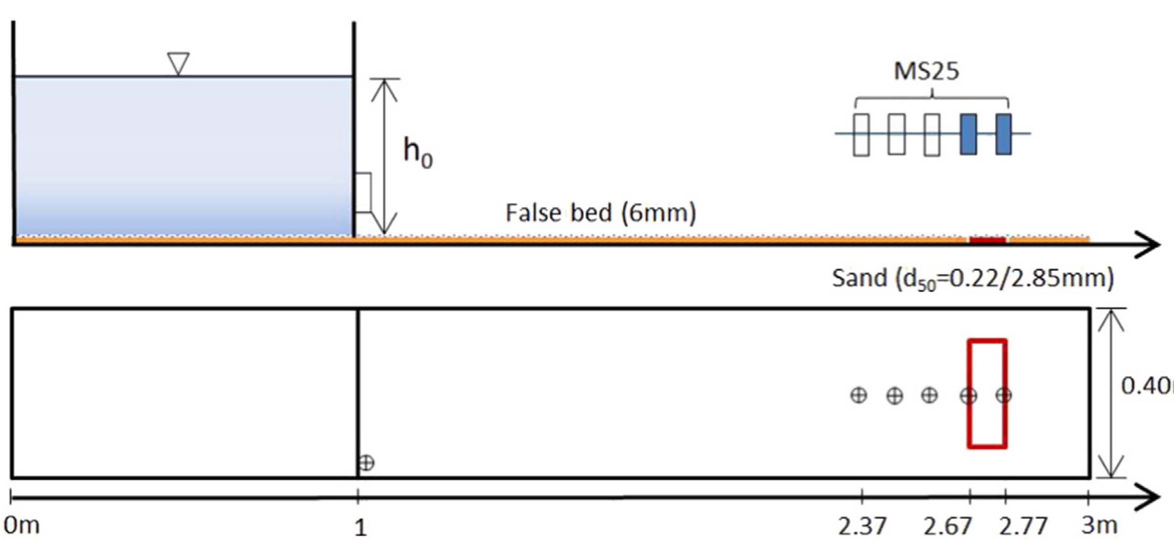

Fig. 1. Elevation view (upper panel) and plan view (lower panel) of dam-break apparatus and instrument layout. The flume pivots about the downstream end, with adjustable slope between $\tan\beta = \pm 0.1$.