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Direct Bed Shear Stress Measurements in Laboratory Swash

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ABSTRACT

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Knowledge of the boundary shear stress in the swash zone is essential for the accurate prediction of sediment transport rates and beach morphology. The variation of bed shear stress over the swash cycle has been investigated directly using a novel shear plate instrument. Laboratory measurements of bed shear stress, flow depth, and fluid velocity were obtained for dam break waves and bore generated swash. For dam break and swash uprush, a large positive (landward) spike in bed shear stress has been measured at the fluid tip followed by a rapid decay throughout the flow interior. The maximum measured negative (seaward) bed shear stress occurring in the swash backwash flow interior is several times smaller than the measured peak uprush bed shear stress. Surface elevation measurements indicate a virtually zero gradient at the uprush tip, a predominately adverse gradient throughout the decelerating uprush interior, and a weakening favourable gradient throughout the entire accelerating backwash. Measured pressure gradients indicate negative (seaward) total acceleration for the majority of the swash cycle. Considering that fluid velocity and total acceleration favours seaward sediment transport for a single swash event, the positive peak in bed shear stress at the uprush tip may in fact be a significant contributor towards the observed uprush sediment transport efficiency.

ADITIONAL INDEX WORDS: *shear plate, dam break, uprush*

INTRODUCTION

For mobile bed environments knowledge of the boundary shear stress is of particular importance to sediment transport modelling. Obtaining accurate measurements or estimates of boundary shear stress in unsteady flow remains a challenge. Difficulties are commonly associated with the design of suitable instrumentation for measuring fluctuating flow characteristics. In the case of near shore coastal environments, the interaction of tidal and wave currents produces turbulent boundary layer velocities and instantaneous bed friction force vectors that fluctuate both in magnitude and direction. Even greater hydraulic complexity is encountered within the swash zone, the region of beach intermittently exposed to the atmosphere due to fluid uprushes and backwashes. In this zone, additional processes that may influence the bed shear stress include bore induced turbulence (JACKSON *et al*., 2004; PRITCHARD AND HOGG, 2005), rapid boundary layer growth (MASSELINK *et al*., 2005), and the effects of infiltration-exfiltration (e.g. BUTT *et al*., 2001).

Sediment transport modelling typically relies on bed shear stress estimates indirectly derived from the near bed logarithmic velocity profile or the quadratic drag law. Close to the bed boundary, the current velocity U varies with the height z above the bed according to the logarithmic velocity profile

$$U(z) = \frac{u_*}{\kappa}\ln\left(\frac{z}{z_0}\right) + D_1 \qquad (1)$$

where u_* is the friction velocity, z_0 is the bed roughness length, and κ is von Karman's constant ($\kappa \approx 0.41$). SCHLICHTING (1979) defines the constant D_1 as $5.5U$ for smooth turbulent flow and $8.5U$ for fully rough turbulent flow. The friction velocity u_* is related to the bed shear stress τ_0 through the relationship $\tau_0 = \rho u_*^2$ where ρ is the fluid density. The bed shear stress is commonly related to the depth-averaged fluid velocity $\overline{U}$ through the friction coefficient C_f

$$\tau_0 = C_f \frac{1}{2}\rho\overline{U}^2 \qquad (2)$$

C_f is related to the widely applied Darcy friction factor f through

$$f = 4C_f \qquad (3)$$

Equation 2 has been shown to successfully predict bed shear stress for steady flow conditions. The applicability of Equation 2 in unsteady flow remains uncertain, although universally applied in wave loading and bed shear stress calculations, usually with a constant friction factor.

In the swash zone the backwash is not simply the opposite of the uprush. Sediment transport modelling in the swash zone that considers transport to be a simple function of velocity (Shield and Energetics models) typically result in predictions of net offshore transport due to uprush/backwash asymmetry (e.g. MASSELINK AND HUGHES, 1998). The stability of most beaches implies that other processes not accounted for by a simple Energetics approach must contribute to onshore directed sediment transport.

The investigation of the vertical structure of swash flows and bed shear stress is limited to a few experimental and field studies.

Laboratory investigations by COX *et al*. (2000) and COWEN *et al*. (2003) reported estimates of shear stress in the inner surf and swash zone with an impermeable bed by fitting mean velocity profile data to the log law. Both COX *et al*. (2000) and COWEN *et al*. (2003) found the uprush C_f to be typically greater than the backwash C_f. However the magnitude of C_f varied between the two studies. Field estimates of bed shear stress and C_f at the uprush tip by HUGHES (1995) and later PULEO AND HOLLAND (2001) differed by order of magnitude. The discrepancies in the description of bed shear stress and estimates of C_f in laboratory and field swash may be attributed to differences between friction at the landward swash edge and in the flow interior, or to the breakdown of logarithmic layer and model assumptions (RAUBENHEIMER *et al.* 2004).

Direct measurements of bed shear stress in experimental open channels or wave flumes are generally restricted to devices that measure the integrated force on a flush mounted shear plate (e.g. RIEDEL AND KAMPHUIS, 1973; GRASS *et al*. 1995) or thermal techniques such as hot film anemometry (e.g. GUST AND SOUTHARD, 1983; PAOLA *et al*. 1986). Some success has been reported with hot film bed shear stress measurements in field swash (CONLEY AND GRIFFIN, 2004). However, the technique is traditionally limited by calibration difficulties and/or obtaining a relationship between heat transfer and bed shear stress.

The present investigation has been prompted by a need for improved knowledge in the applicability of laboratory and field studies of bed shear stress in swash flows. A shear plate with a fundamental design based on the UCL shear cell (GRASS *et al*. 1995) is used to obtain direct shear stress measurements in laboratory dam break and swash flows. The dam break problem and the effect of friction is of interest here since an analogy can be drawn with the run-up of a solitary wave (CARRIER *et al*. 2003) or with swash motion following bore collapse (SHEN AND MEYER, 1963; PEREGRINE AND WILLIAMS, 2001; PRITCHARD AND HOGG, 2005). The key difference with previous shear cell measurements is the "dry/wet" intermittent nature of the flow.

METHODS

Experiments were conducted at The University of Queensland Hydraulics Laboratory using two facilities – a dam break flume and a solitary wave flume. In each facility a novel shear plate, suitable for use in dry/wet flow, was installed allowing direct shear stress measurement (refer to BARNES AND BALDOCK, 2006 for diagrams of experimental flumes and shear plate).

The aluminium shear plate is 0.1 m long, 0.25 m wide and 0.001 m thick. Four stainless steel tubular legs are clamped to the underside of the plate and extend to the base of the shear plate's casing (referred herein as 'cell') where they are fixed. Below the plate two bars fitted with stainless steel ball bearing rollers extend longitudinally offering support against hydrostatic loading. A positive displacement approach is adopted whereby the applied shear force causes the plate to be displaced in the horizontal direction of the shear. To allow for the displacement, a 0.002 m gap exists between the longitudinal plate edges and the cell casing. Any horizontal shear applied across the plate causes the four support legs to flex in the direction of the shear, shifting the plate a distance directly proportional to the force. The horizontal displacement vector of the shear plate is measured by a single Indikon Eddy-current Proximity Probe aligned perpendicular to a target plate attached to the underside of the shear plate.

During operation the shear cell is filled with water. The pressure that exists in the gap at each longitudinal plate edge is measured via two Druck PMP 317-2780 pressure transducers with ±0.15% accuracy (GE DRUCK, 2006). The pressure that exists in the gaps is a secondary force capable of producing work on the small area of the plate's edge (i.e. plate width × thickness = 0.00025 m^2). The additional force in the gaps must be removed from the total force measured by the shear plate in order to resolve the shear stress.

Dam break experiments were conducted in a tilting flume 3 m long, 0.4 m wide and 0.4 m high. The flume has an impermeable PVC bed (roughness height, $k_s \approx 0.1$ mm) and clear glass walls. One end of the flume is permanently closed. The other end is open to allow overtopping. A dam gate can be located at any position along the flume's length acting to hold a reservoir of desired volume. The gate is PVC, 12 mm thick, with a silicon seal at the base and sides. The seal together with a small amount of silicon grease eliminate any leakage from the reservoir. The bed in front of the gate is completely dry. Connected to the gate is a pivoting arm that opens and closes the gate. The gate is operated manually. Video analysis indicates that the gate opens to a height > 0.2 m in approximately 0.12 s.

Solitary wave (bore) experiments were conducted in a wave flume 0.85 m wide, 0.75 m high, with a bore propagation distance of approximately 8 m. The flume has an impermeable bed, glass walls, and 1:10 beach slope constructed from smooth, painted marine plywood. A single bore is generated by a piston wave maker with bore height H controlled by the piston stroke length L and speed V. Provided the piston stroke is of sufficient speed the bore forms at the wave maker paddle and is assumed fully developed upon reaching the shoreline.

Direct shear stress τ_0 measurements at laboratory swash scale were obtained using the shear plate installed flush with the bed. Free surface elevation η was measured at various locations using an array (0.1 m spacing) of non-intrusive Mic+25 Microsonic (MS) acoustic sensors. Instantaneous free-stream velocity components U_x and U_y were measured using a SonTek micro Acoustic Doppler Velocimeter (ADV) 16 MHz. The ADV has a two-dimensional side looking head and was located to the side of the shear plate for dam break experiments and at the beach toe for bore experiments. A single MS sensor was aligned above the ADV sample volume to measure water surface elevation.

Experiments were conducted for a range of initial depths and distances to the fixed measurement location relative to the still-water line (SWL). Consequently, the variation of shear stress with time was investigated at various positions within the laboratory swash zone.

Data acquisition and instrument synchronisation was performed using LabView v7.1 and Horizon ADV v.1.04. ADV external synchronisation error is expected to be < 1 ms (SONTEK, 2001). Velocity data was post-processed using WinADV v2.010. Velocity samples with a signal correlation coefficient < 70 % or a signal-to-noise ratio < 15 dB were disregarded.

RESULTS

The typical temporal variation of h and τ_0 for a dam break wave on horizontal dry bed with initial reservoir depth D = 0.2 m is shown in Figure 1. Time t = 0 s is when the dam gate is opened. Instrument location x = 1.15 m is measured from the dam gate. Depth h obtained using a MS sensor above the shear plate clearly indicates the region at the surge tip where the effects of resistance are important (e.g. DRESSLER, 1954). The maximum shear stress τ_0 is measured at the surge tip followed by a rapid decay to a quasi-constant τ_0 value for t > 4 s. Figure 1a shows the predicted depth using the ANUGA coastal inundation model (NIELSEN *et al*., 2005) modified to simulate the dam break flume.

The temporal variation of laboratory swash bed shear stress at x = 0 m and x = 0.47 m is presented in Figure 2 and Figure 3. Figure 2a and 3a show the total force F_T measured by the shear plate (crosses) and the contribution to the total force due to the pressure

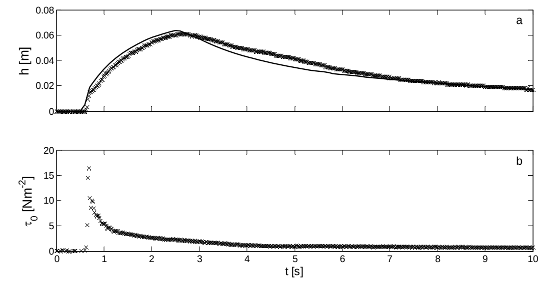

Figure 1. Horizontal dam break wave at x = 1.15 m. Initial reservoir depth D = 0.2 m. (a) Measured (crosses) and modelled (solid line) depth h. (b) Measured shear stress τ_0.

force F_P acting in the gaps at the longitudinal edges of the plate (dot line). The shear stress time series (Figure 2b and 3b) is obtained by removing the pressure force from the total measured force and integrating over the area of the shear plate (thus resolving the force due to shear only).

Shear stress time series show a maximum positive (landward directed) shear stress at the fluid tip followed by a rapid decay throughout the decelerating uprush interior. Following flow reversal (approximately t = 4 s) the maximum negative (seaward directed) shear stress occurs late in the accelerating backwash phase. The measured shear stress tends to zero as the backwash flow depth reduces and the relative roughness increases.

Surface elevation was resolved using pressure transducers and/or MS sensors positioned at the seaward and landward edges of the shear plate. Considering the relationship between pressure gradient, surface elevation, and fluid acceleration, Euler's equation yields for depth averaged horizontal flow (e.g. DEAN AND DALRYMPLE, 1991)

$$\frac{DU}{Dt} = \left(\frac{\partial U}{\partial t} + U\frac{\partial U}{\partial x} \right) = -\frac{1}{\rho}\frac{\partial p}{\partial x} = -g\frac{\partial \eta}{\partial x} \qquad (4)$$

where DU/Dt is the total acceleration (the local acceleration, $\partial U/\partial t$, plus the convective acceleration, $U\partial U/\partial x$), $\partial p/\partial x$ is the pressure gradient, g is the acceleration due to gravity, and $\partial\eta/\partial x$ is the fluid surface elevation with respect to an arbitrary horizontal datum (refer BALDOCK AND HUGHES, 2006). Considering Equation 4 with x positive landward, a positive pressure gradient corresponds to a seaward dipping water surface slope and therefore negative total acceleration. A negative pressure gradient corresponds to a landward dipping water surface slope and therefore a positive total acceleration.

Figure 2c shows in the region of the SWL (x = 0 m) a landward dipping surface exists for $t \approx 1 - 2.5$ s. For this short period of bore collapse and subsequent uprush directed flow, the landward dipping surface slope will lead to a favourable pressure gradient and perhaps an enhancement of the landward directed shear stress. For $t > 2.5$ s the surface slope is seaward dipping leading to an adverse pressure gradient for the remainder of the uprush phase. Following flow reversal, a favourable pressure gradient exists throughout the entire backwash. Figure 3c shows that in the lower swash region (x = 0.47 m) a seaward dipping surface slope exists for the entire swash cycle (with the exception of the fluid tip where no gradient was detected). During this uprush period, the seaward dipping surface slope will lead to an adverse pressure gradient and perhaps a reduction of the shear stress. Further work is required to better understand the implications of pressure gradients on the developing swash boundary layer.

DISCUSSION

Great difficultly is associated with obtaining reliable velocity measurements at the uprush tip and at the end of the backwash in field and laboratory swash. The swash challenges even state-of-the-art instrumentation due to wetting and drying, bubbly flows, and shallow flow depths. Figure 4a highlights the difficulties in obtaining velocity measurements at the tip of a dam break wave (analogous to a swash uprush) using an ADV. Reliable U_x samples were only obtained for approximately $t > 5$ s. Complications are associated with the intrusive nature of the ADV probe and the response time of the instrument (once suddenly immersed in the fluid). Work is underway obtaining direct shear stress measurements in conjunction with velocities resolved using Particle Image Velocimetry (PIV). The PIV technique will provide a more complete swash velocity time series, but still cannot reliably resolve velocities at the fluid tip, particularly for smooth beds.

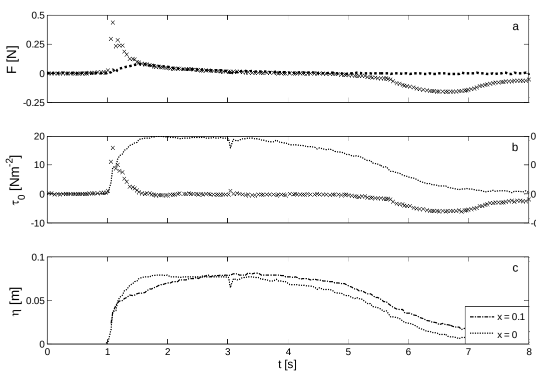

Figure 2. Laboratory swash cycle time series at x = 0 m. (a) Measured total force F_T (crosses) and pressure force F_P (dot line). (b) Corrected shear force (crosses) and depth h (dash line). (c) Surface elevation η (relative to the SWL) across the shear plate.

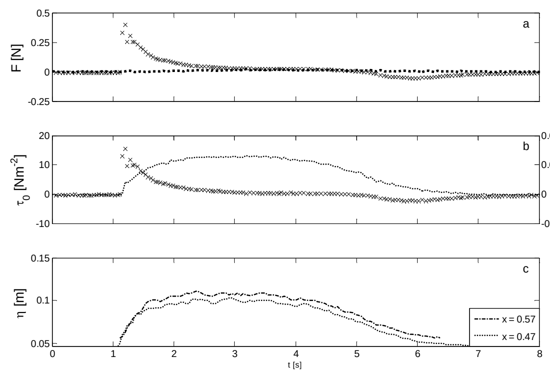

Figure 3. Laboratory swash cycle time series at x = 0.47 m. (a) Measured total force F_T (crosses) and pressure force F_P (dot line). (b) Corrected shear force (crosses) and depth h (dash line). (c) Surface elevation η (relative to the SWL) across the shear plate.

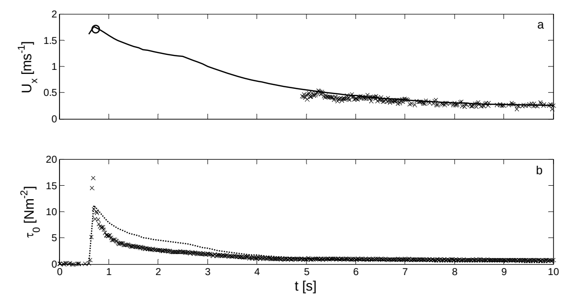

Figure 4. Horizontal dam break wave at x = 1.15m. D = 0.2m. (a) Measured (crosses), dam tip celerity (circle) and modelled (solid line) velocity U_x. (b) Measured (crosses) and predicted (dash line; k_s = 0.1 mm) shear stress.

For the present investigation, dam break wave shear stress measurements were analysed using ANUGA modelled velocities. Figure 4a shows the modelled U_x velocity validated with the reliable ADV measurements available (the depth time series for the event in Figure 4 is presented in Figure 1a). The model provides accurate predictions of the flow depth and flow velocity, including the influence of the negative wave reflected from the closed end of the flume. Assuming that in the region of the shallow dam break tip the flow velocity is approximately equal to the dam surge celerity, a single sample for data model comparison may be obtained using the spaced MS sensors. The circle at the velocity peak in Figure 4a was obtained via five MS sensors aligned in an array (0.1 m spacing). The wave tip was taken to have "arrived" when the MS sensors measured a flow depth h > 0.01 m. The wave tip celerity was then obtained by analysing the time taken to propagate between sensors, and matches well with the model predictions.

The Colebrook-White formula is commonly used to estimate friction coefficients in fully-developed turbulent pipe and open channel flow. HENDERSON (1966) presented the Colebrook-White formula for free-surface flow as

$$\frac{1}{\sqrt{C_f}} = -4.0 \log\left(\frac{k_s}{12R} + \frac{1.25}{\mathrm{Re}\sqrt{C_f}}\right) \qquad (5)$$

where k_s is the roughness height (k_s = 0.1 mm for smooth PVC/glass flume), R is the hydraulic radius, and Re = U_xR/ν is the Reynolds number. Using the measured depth h, flume dimensions, and the modelled velocity, R and Re may be resoled for each time step and therefore a time-varying friction factor based on Equation 5 may be obtained.

Figure 4b shows the measured temporal variation of τ_0 for a dam break wave on a dry horizontal bed compared to the predicted shear stress using a time varying friction factor based on Equation 5 and following Equation 2. The initial peak in measured shear stress shown by the crosses in Figure 4b is approximately double that calculated from the instantaneous value from Equation 5. Note that the shear stress drops very rapidly behind the tip, much faster than is predicted using either the local C_f or a constant C_f. This implies that it may be inappropriate to calculate the shear stress based on conventional steady flow friction factors close to the dam tip. If the analogy between dam break flow and swash uprush exists, Figure 4b also suggests instantaneous sediment loads under swash need to be determined using an instantaneous C_f.

Using the measured shear stress and modelled velocity the behaviour of the friction coefficient C_f can be investigated though back calculation of Equation 2. Figure 5 shows the trend between C_f and the flow Reynolds number (Re = U_xh/ν). For Eulerian measurements at x = 0.85, 1.15, and 1.45 m there is a clear reduction in friction coefficient with increasing Reynolds number. The mean C_f value of approximately 0.011 for a dam break wave is consistent with inferred friction coefficients for laboratory swash uprush presented by COWEN et al. (2003) (0.0127 and 0.0162 for plunging and spilling uprush respectively) and is of the same magnitude as frictions factors inferred throughout various investigations (e.g. COX *et al.,* 2000; RAUBENHEIMER *et al.,* 2004). Direct measurements of swash shear stress in the field by CONLEY AND GRIFFIN (2004) suggested a significantly smaller mean uprush C_f value of 0.0037

Figure 6 presents the ensemble average (5 swashes) of the maximum landward and seaward directed shear stress at various fixed locations for a laboratory swash cycle on an impermeable 1:10 slope beach. Positive τ_0 values are landward directed and negative τ_0 values are seaward directed, x is positive landward. Maximum seaward directed shear stress was measured at the region of bore collapse (SWL, x = 0 m) and maximum landward directed shear stress was measured in the lower swash region (x = 0.27 m). This is consistent with COX *et al*. (2000) who observed the inferred shear stress to increase between the SWL and the lower swash region. This region is likely to be a significant contributor to the landward transport of sediment with high shearing stress, bore induced turbulence, and landward direct pressure gradients.

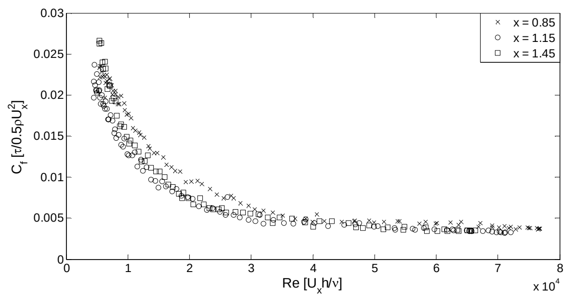

Figure 5. Back-calculated C_f using measured shear stress τ_0 and modelled U_x for dam break surge on a dry horizontal bed at x = 0.85, 1.15, and 1.45 m.

CONCLUSION

Results of the initial analysis of direct bed shear stress measurements using a novel shear plate in laboratory scale dam break flows and solitary wave swash have been presented. For a smooth, impermeable, horizontal bed, comparison between measured and calculated shear stress suggest the shear stress is not well predicted by conventional steady flow friction factors in the dam break wave fluid tip (analogous to the swash uprush tip). The peak measured shear stress at the fluid tip is approximately twice that predicted using steady flow friction factors evaluated at corresponding Reynolds numbers and relative roughness and reduces more rapidly than predicted. This large landward directed peak of short duration may be a significant contributor to the observed uprush sediment transport efficiency.

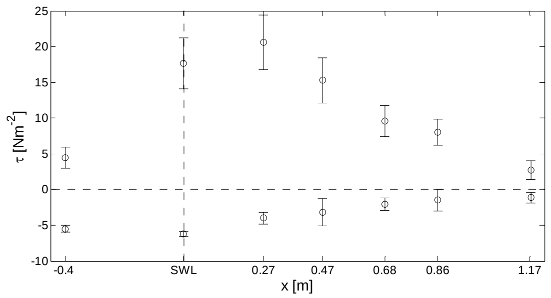

Figure 6. Ensemble average of maximum measured shear stress in the inner surf and swash zone. Positive and negative τ indicates landward and seaward directed stress respectively. Error bars represent two standard deviations from the mean.

The high shear stress at the fluid tip is most likely a result of a very thin boundary layer which develops as the bed is first wetted. Further work is required to model this process. For the internal flow region, the flow history should be considered. In this instance, Reynolds numbers and relative roughness may be more appropriately defined in terms of the integrated products of velocity and displacement, following the flow, and relative roughness with respect to the boundary layer thickness, δ, as opposed to the depth. Future work will examine this issue.

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