Coastal Engineering 56 (2009) 853–867

Contents lists available at ScienceDirect

Coastal Engineering

journal homepage: www.elsevier.com/locate/coastaleng

# Direct bed shear stress measurements in bore-driven swash

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ARTICLE INFO

*Article history:*
Received 15 October 2008
Received in revised form 19 March 2009
Accepted 6 April 2009
Available online 8 May 2009

*Keywords:*
Bed shear stress
Shear plate
Swash zone
Friction coefficient
Sediment transport
Beach morphodynamics
Boundary layer

ABSTRACT

Direct measurements of bed shear in the swash zone are presented. The data were obtained using a shear plate in medium and large-scale laboratory bore-driven swash and cover a wide range of bed roughness. Data were obtained across the full width of the swash zone and are contrasted with data from the inner surf zone. Estimates of the flow velocities through the full swash cycle were obtained through numerical modelling and calibrated against measured velocity data. The measured stresses and calculated flow velocities were subsequently used to back-calculate instantaneous local skin friction coefficients using the quadratic drag law. The data show rapid temporal variation of the bed shear stress through the leading edge of the uprush, which is typically two–four times greater than the backwash shear stresses at corresponding flow velocity. The measurements indicate strong temporal variation in the skin friction coefficient, particularly in the backwash. The general behaviour of the skin friction coefficient with Reynolds number is consistent with classical theory for certain stages of the swash cycle. A spatial variation in skin friction coefficient is also identified, which is greatest across the surf-swash boundary and likely related to variations in local turbulent intensities. Skin friction coefficients during the uprush are approximately twice those in the backwash at corresponding Reynolds number and cross-shore location. It is suggested that this is a result of the no-slip condition at the tip leading to a continually developing leading edge and boundary layer, into which high velocity fluid and momentum are constantly injected from the flow behind and above the tip region. Finally, the measured stress data are used to determine the asymmetry and cross-shore variation in potential sediment transport predicted by three forms of sediment transport formulae.


## 1. Introduction

Prediction of sediment transport in the swash zone remains a major challenge in coastal engineering. Despite recent advances in theoretical and numerical modelling (e.g. Kobayashi and Johnson, 2001; Pritchard and Hogg, 2005, Karambas, 2006; Calantoni and Puleo, 2006; Baldock et al., 2008) and detailed field observations of sediment transport and beach morphology (Masselink et al., 2005; Weir et al., 2006; Aagaard et al., 2006; Austin and Masselink, 2006; Hsu and Raubenheimer, 2006) models for beach profile evolution are poor and usually unable to correctly estimate net sediment transport directions and net deposition (see Masselink and Puleo, 2006 and Brocchini and Baldock, 2008 for recent reviews). This is despite the fact that relatively simple sediment transport models appear reasonably robust predictors of gross sediment transport rates in the swash zone (e.g. Masselink and Hughes, 1998; Butt et al., 2004). While settling of pre-suspended sediment entering the swash has an important role to play in the net transport (e.g. Pritchard and Hogg, 2005; Alsina et al., 2005), the boundary shear stress is the fundamental and dominant driving mechanism for both bed load and suspended load (e.g. Nielsen, 1992). Bed shear stress is fundamental to improving swash sediment transport predictions, but present models tend to be based on approaches used for steady or oscillatory wave flows, neither of which are necessarily appropriate in the swash zone (Elfrink and Baldock, 2002; Masselink et al., 2005).

Measurements of bed shear stress in the swash are most often obtained indirectly from boundary layer velocity profile measurements. Controlled experimental investigations combined with advances in instrumentation and modelling ability have significantly furthered knowledge of boundary layer structure in steady and oscillatory flow regimes. In contrast, measurements of the boundary layer within swash remains a challenge, although Petti and Longo (2001), Cox et al. (2000), Archetti and Brocchini (2002), Cowen et al. (2003) and Raubenheimer et al. (2004) provide data close to the surf-swash boundary. However, significant difficulties with this approach arise at the leading and trailing edges of the swash, as a result of intermittent bubbly flow and very shallow flow depths. Conley and Griffin (2004) report hot-film measurements of swash bed shear stress in the field, a particularly challenging environment. Their data indicate friction coefficients over mobile sand beds an order of magnitude lower than other estimates from field data, so some uncertainty remains. In addition, the measurement location within the swash zone was not reported. As a result, a quantitative understanding of the cross-shore variation in swash zone bed shear stress is lacking.

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doi:10.1016/j.coastaleng.2009.04.004

The present paper addresses these issues by providing the first comprehensive data set of direct stress measurements obtained using a shear plate within the swash zone. The data are obtained from medium and large-scale experimental facilities and include a wide range of different bed roughness. Swash zone friction coefficients are back-calculated using a combination of measured and modelled flow velocities. This paper is organised as follows. Section 2 provides a review of relevant theory and previous work. Section 3 outlines the experimental arrangement, instrumentation and flow conditions. Examples of the measured shear stresses are presented in Section 4, together with the modelling and analysis techniques applied to calculate friction coefficients. The detailed experimental results are presented in Section 5, and include the temporal variation of shear stress, Reynolds number and friction coefficient during individual swash flows, and the spatial variation of the maximum and minimum shear stresses and friction coefficients. The influence of bed roughness is also illustrated. Final conclusions follow in Section 7.

## 2. Previous work

Sediment transport modelling typically relies on bed shear stress estimated from the near bed logarithmic velocity profile. Close to the bed boundary, the fluid horizontal velocity $U$ varies with height $z$ above the bed according to the logarithmic velocity profile

$$U(z) = \frac{u*}{\kappa}\ln\left(\frac{z}{k_s}\right) + D_1. \quad (1)$$

where $u_*$ is the friction velocity, $k_s$ is the bed roughness length, and $\kappa$ is von Karman's constant (typically $\kappa = 0.40$). Schlichting and Gersten (2000) define the constant $D_1$ as $5.5u_*$ for smooth turbulent flow and $8.5u_*$ for fully rough turbulent flow. Eq. (1) is commonly referred to as the law-of-the-wall or the log-law. The friction velocity $u_*$ is related to the bed shear stress $\tau_0$ through the relationship $\tau_0 = \rho\, u_*^2$ where $\rho$ is the fluid density. However, the velocity profile is difficult to measure during swash, especially close to the fluid tip and towards the end of the backwash when depths are very small. This makes application of the log-law to determine swash bed shear stress problematic, except for highly controlled experimental conditions.

For uniform steady flow bed shear stress is related to the free-stream fluid velocity through a friction coefficient $C_f$ (sometimes attributed to Fanning) via the quadratic relation

$$\tau_0 = \rho u_*^2 = C_f \frac{1}{2}\rho U^2. \quad (2)$$

Eq. (2) is widely applied for bed shear stress calculations under waves using a constant value friction coefficient. However, $C_f$ is a function of Reynolds number and relative bed roughness, both of which vary substantially with time and space in the case of swash flow. Recent work by Nielsen and Callaghan (2003) and Nielsen (2006) has modified the relationship between $\tau_0$ and $C_f$, by accounting for temporal acceleration or allowing a time-varying friction coefficient. While a time-varying friction coefficient in the swash (using Eq. (2)) is well illustrated by Cowen et al. (2003), high shoreward temporal accelerations do not occur in swash, except close to the location of bore collapse (Hughes and Baldock, 2004; Baldock and Hughes, 2006; Puleo et al., 2007).

Swash friction coefficients have been inferred from bed shear stress estimates obtained from fitting the log-law to observed velocity profiles (e.g. Cox et al., 2000; Archetti and Brocchini, 2002; Cowen et al., 2003; Raubenheimer et al., 2004; Hondebrink, 2006), or direct bed shear stress measurements (Conley and Griffin, 2004). The values of $C_f$ obtained vary significantly ($0.001 < C_f < 0.054$). The variance is partly due to the method used to determine $C_f$, the experimental conditions, and the locations within the swash where measurements were made. A common finding is that $C_f$ differs between uprush and backwash, with Cox et al. (2000), Archetti and Brocchini (2002), Cowen et al. (2003), and Conley and Griffin (2004) presenting time-averaged uprush coefficients $C_{fu}$ that are typically greater than the time-averaged backwash coefficients $C_{fb}$. Conversely, based on field measurements of swash velocity profiles, Raubenheimer et al. (2004) report no statistical difference between uprush and backwash friction coefficients. Some evidence suggests $C_f$ may vary temporally and spatially over the swash cycle. However, only Cowen et al. (2003) and Hondebrink (2006) present detailed time-series of friction coefficients.

Despite providing a workable model, the law-of-the-wall may not actually be applicable at all times throughout the highly unsteady and non-uniform swash flow, especially at times of bore arrival, at flow reversal and towards the end of the backwash when flow depths are very shallow. Furthermore, inferring $\tau_0$ from the log-law relies on precise knowledge of the elevation above the bed, $z$, where velocity measurements are taken. Accurately determining this in the field is difficult and a $\pm 1$ cm error can lead to $C_f$ being over- or under-predicted by 40% (Raubenheimer et al., 2004). Conley and Griffin (2004) attempted to address these issues via hot-film measurements. However, their measurements yielded friction coefficients that are an order of magnitude lower than friction coefficients obtained from other field data (e.g. Raubenheimer et al., 2004). Co-located flow velocities were not measured by Conley and Griffin and the measurement location within the swash zone was not reported; these add to the uncertainties in the friction coefficients produced. Nevertheless, their result showing higher friction coefficients in the uprush than in the backwash is consistent with some previous results (e.g. Cox et al., 2000; Archetti and Brocchini, 2002; Cowen et al., 2003). An alternative to the log-law and hot-film approaches is direct measurement of the bed shear stress via the drag on a shear plate, which has been successfully applied under wave motion (Grass et al., 1995; Myrhaug et al., 2001). Barnes and Baldock (2007) reported the development of a shear plate designed specifically for deployment in the swash zone and showed examples of direct stress measurements and friction coefficients from smooth bed dam-break flows and swash flows. The shear plate enables bed shear stress measurement from the moment of bore arrival to the very end of the backwash. The fact that the plate measures bed shear stress at the very beginning and end of the swash cycle is particularly important in the context of sediment transport since the highest velocities and bed shear stresses occur at these times.

## 3. Experimental setup

Two series of laboratory experiments are presented:

1. Large-scale solitary bore-driven swash experiments carried out using the University of Aberdeen (UA) swash facility;
2. Medium scale solitary bore-driven swash experiments carried out in the University of Queensland (UQ) wave flume.

In both cases a shear plate was used to make direct measurements of bed shear stress; corresponding measurements were made of the swash flow depths and velocities, as described as follows.

### 3.1. The swash shear plate

The design of the shear plate used to directly measure bed shear stress is based on the University College London (UCL) shear cell developed by Grass et al. (1995). Cross sectional diagrams of the shear cell are shown in Fig. 1. Within the Perspex cell casing, four thin tubular sway legs support a removable smooth aluminium shear plate, 0.1 m long, 0.25 m wide and 0.73 mm thick, with mass 94 g. The four legs are clamped to the underside of the plate and extend to the base of the cell where they are fixed. The leg stiffness provides the restoring force and