Field observations of instantaneous water slopes and horizontal pressure gradients in the swash-zone

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Abstract

Field observations of instantaneous water surface slopes in the swash zone are presented. For free-surface flows with a hydrostatic pressure distribution the surface slope is equivalent to the horizontal pressure gradient. Observations were made using a novel technique which in its simplest form consists of a horizontal stringline extending seaward from the beach face. Visual observation, still photography or video photography is then sufficient to determine the surface slope where the free-surface cuts the line or between reference points in the image. The method resolves the mean surface gradient over a cross-shore distance of 5 m or more to within \( \pm 0.001 \), or 1/20th \( \pm 1/100 \)th of typical beach gradients. In addition, at selected points and at any instant in time during the swash cycle, the water surface slope can be determined exactly to be dipping either seaward or landward. Close to the location of bore collapse landward dipping water surface slopes of order 0.05–0.1 occur over a very small region (order 0.5 m) at the blunt or convex leading edge of the swash. In the middle and upper swash the water surface slope at this leading edge is usually very close to horizontal or slightly seaward. Behind the leading edge, the water surface slope was observed to be very close to horizontal or dipping seaward at all times throughout the swash uprush. During the backwash the water surface slope was observed to be always dipping seaward, approaching the beach slope, and remained seaward until a new uprush edge or incident bore passed any particular cross-shore location of interest. The observations strongly suggest that the swash boundary layer is subject to an adverse pressure gradient during uprush and a favourable pressure gradient during the backwash. Furthermore, assuming Euler’s equations are a good approximation in the swash, the observations also show that the total fluid acceleration is negative (offshore) for almost the whole of the uprush and for the entire backwash. The observations are contrary to recent work suggesting significant shoreward directed accelerations and pressure gradients occur in the swash (i.e., \( \hat{\partial}u/\hat{\partial}t > 0 \sim \hat{\partial}p/\hat{\partial}x < 0 \)), but consistent with analytical and numerical solutions for swash uprush and backwash. The results have important implications for sediment transport modelling in the swash zone.

Keywords: Swash; Long wave runup; Pressure gradients; Flow acceleration; Boundary layers; Sediment transport; Bores; Dam break

1. Introduction

The hydrodynamics in the swash zone govern sediment transport mechanisms during wave run-up and run-down, which in large part control beach face morphology. The swash zone therefore plays an...
important role in littoral sediment transport, particularly during episodes of beach erosion and recovery (Elfrink and Baldock, 2002). In particular, the sediment transport in the upper swash zone is important for both berm building and beach scarping. Prediction of sediment transport in the swash zone is complicated by different transport modes (Horn and Mason, 1994), high concentrations of sediment (Hughes et al., 1997a; Osborne and Rooker, 1999) and diverging flow (Hibberd and Peregrine, 1979; Raubenheimer and Guza, 1996; Baldock and Holmes, 1997). These are combined with high flow velocities and very shallow water depths (Hughes and Baldock, 2004). Seaward and shoreward boundary conditions may also modify the net sediment flux in the swash zone. Examples include the advection of turbulence and sediment from the surf zone into the swash (Hughes et al., 1997b; Kobayashi and Johnson, 2001; Jackson et al., 2004; Pritchard and Hogg, 2005) or the overtopping of beach berms (Baldock et al., 2005). Butt and Russell (2000) and Elfrink and Baldock (2002) provide extensive reviews of these issues, as well as swash zone hydrodynamics and sediment transport in general.

A significant and unresolved issue is the physically inconsistent nature and/or poor performance of sediment transport models for the swash zone, particularly in cases where there is zero net transport or shoreward net transport (i.e. the case of an equilibrium or an accreting beach, respectively). To date, most swash sediment transport models are based on derivatives of the Energetics approach (Bagnold, 1966; Bailard, 1981), describing the bed load, suspended load or total load transport as a simple function of velocity, i.e., $u^n$ or equilibrium models (Pritchard and Hogg, 2005). If friction factors and/or transport coefficients are held constant for uprush and backwash, this invariably results in predictions of net offshore transport as a result of the flow asymmetry in the swash (e.g. Masselink and Hughes, 1998; Puleo et al., 2000, 2001). This is not realistic, given the stability of most beaches, and provides no mechanism for net shoreward transport and sediment accretion on the upper beach.

Recent modelling approaches to address this issue have considered modifications to the bed shear stress or particle stability by accounting for infiltration and exfiltration effects (Turner and Masselink, 1998; Baldock et al., 2001; Butt et al., 2001), modified descriptions for the friction factor or boundary layer to account for turbulence (Puleo and Holland, 2001; Butt et al., 2001), improved descriptions of suspended sediment behaviour, particularly sediment advected into the swash from bore collapse (Hughes et al., 1997b; Jackson et al., 2004; Pritchard and Hogg, 2005) and finally the effects of local (Eulerian) fluid accelerations or horizontal pressure gradients (Nielsen, 2002; Puleo et al., 2003). The latter may modify the transport rates directly (see Nielsen, 1992) or serve as a proxy for turbulent effects that are not well understood (Puleo et al., 2003).

Given that the total horizontal force on sediment particles comprises the sum of a drag force and inertial (pressure) forces (Nielsen, 1992), the direction of pressure gradient forces in the swash is of fundamental importance for a correct description of the hydrodynamics and sediment dynamics. While the free stream pressure gradient in oscillatory flow causes the bed shear stress to lead the free stream flow velocity, classical boundary layer theory assumes the free stream pressure (and gradient) is imposed onto, and across, the boundary layer (Schlichting, 1979). Whether the swash boundary layer should be regarded as a variation of an oscillatory boundary layer or as a boundary layer more equivalent to that in unidirectional flows remains to be established (see discussions by Cowen et al., 2003; Masselink et al., 2005). The direction of the free stream pressure gradient in the swash is of fundamental importance in this regard. However, there are no direct measurements of instantaneous horizontal pressure gradients in the swash, although they may be derived from some limited water depth measurements (see Section 2 below).

The present paper addresses this point and presents field observations of the instantaneous water surface slopes in the swash zone using a novel technique. For free-surface flows with a hydrostatic pressure distribution the surface slope is equivalent to the horizontal pressure gradient. Furthermore, if shear stresses within the fluid are small, Euler’s equations apply and the horizontal pressure gradient is directly proportional to the total fluid acceleration (local plus convective, e.g. Dean and Dalrymple, 1991; see Section 2.2). The novel measurement technique therefore avoids the significant complication of strong vertical gradients in the flow velocity. Field observations are presented from four different sites encompassing a large range of beach slopes and swash conditions. The results are presented in photographic form,
which best illustrate the data, and in graphical form. They include water surface slopes from the inner surf zone, through bore collapse and uprush, and the end of the backwash. Section 2 reviews previous work and considers data and numerical model results relevant to the present study. Simple relations are also derived from the swash solution of Peregrine and Williams (2001) to delimit regions of the swash with different flow characteristics and acceleration. Section 3 describes the methodology and field sites and the observations are presented and discussed in Section 4. Final conclusions follow in Section 5.

2. Previous work and governing equation

2.1. Flow characteristics

Swash may be forced by non-breaking waves or broken waves (bores), with the resulting motion described by two different solutions to the nonlinear shallow water equations (NLSWE). For non-breaking waves, typically standing long waves, the solution of Carrier and Greenspan (1958) predicts a shoreward dipping water surface for short durations at the beginning and end of the swash cycle. While standing long waves may be an energetic part of the total swash motion, in most practical cases the long waves co-exist with broken short waves, and separating the two components in the swash is not trivial (Baldock and Huntley, 2002). In any event, the long waves may themselves be breaking (Battjes et al., 2004). The broken waves form bores in the surf zone and collapse upon reaching a location with zero water depth, carrying turbulence and suspended sediment into the swash (Masselink and Hughes, 1998).

Shen and Meyer (1963) presented an analytical solution to the NLSWE describing swash motion following bore collapse. This has been extensively investigated under laboratory and field conditions (Yeh et al., 1989; Hughes, 1992, 1995; Baldock and Holmes, 1997, 1999; Holland and Puleo, 2001, Hughes and Baldock, 2004). Peregrine and Williams (2001) extended this solution to obtain the kinematics over the full swash zone, with the same solution further extended by Pritchard and Hogg (2005) to calculate suspended sediment transport in the swash. Numerical solutions of the NLSW equations (Hibberd and Peregrine, 1979; Kobayashi et al., 1989) also provide a good description of bore driven swash (Raubenheimer and Guza, 1996; Raubenheimer, 2002). The Peregrine–Williams solution predicts very brief periods of shoreward total acceleration as the bore collapses, although they note that strictly the solution is not valid in this region. Only seaward total acceleration is predicted thereafter. The local acceleration is predicted to be seaward at all times (see Section 2.2 below). The numerical calculations of Hibberd and Peregrine (1979) show similar results; for a uniform bore collapsing at the shore the local Eulerian velocity reduces throughout the uprush, followed by an increasingly negative velocity (negative local acceleration) throughout the backwash until the formation of a backwash bore. The water surface dips seaward everywhere except during bore collapse and the formation of a backwash bore or shear wave (Peregrine, 1974).

These analytical and numerical results are consistent with laboratory data that show a seaward dipping water surface for most of the swash cycle (Baldock and Holmes, 1997) and little evidence of positive (shoreward) local fluid accelerations (Petti and Longo, 2001). Concurrently, field data obtained with impellor current meters show a rapid increase to a maximum velocity just after inundation during the uprush, and a slower decrease toward zero velocity at the end of the backwash (e.g. Masselink and Hughes, 1998; Puleo et al., 2000, 2003). This has been interpreted as representing large onshore directed accelerations at these phases of the swash cycle, with the local acceleration a surrogate for a pressure gradient (Puleo et al., 2003). However, given that impellor current meters must start from a stationary situation, an apparent local acceleration will inherently be recorded at the beginning of the uprush. In contrast, field data obtained by Acoustic Doppler Velocimetry (ADV) show no onshore directed accelerations in the swash provided that appropriate data quality thresholds are applied and the velocity record is correctly undefined when the sensor is out of the water (e.g. Raubenheimer, 2002, Hughes and Baldock, 2004). It should be noted that measurements just seaward of the inner surf/swash boundary do show the accelerations expected under non-breaking or broken waves (e.g. Baldock and Holmes, 1997; Raubenheimer, 2002; Raubenheimer et al., 2004).

2.2. Theoretical description and momentum equation

The Peregrine and Williams (2001) analytical swash solution provides a simple description of the flow characteristics in the \( x-t \) plane. Their solution
gives the non-dimensional bed parallel velocity, $u(x,t)$ as

$$u(x,t) = \frac{2}{3t}(t - t^2 + x),$$

(1)

where $x$ is measured along the slope (we have retained their nomenclature despite the conflict with the usual horizontal coordinate $x$). They illustrate the locus of critical flow ($u = c$, where $u$ is the flow velocity and $c$ is the shallow water wave speed) during the uprush, given by the curve $x = 1/2t^2$, and where $x$ and $t$ are non-dimensional cross-shore distance (positive shoreward) and time, respectively (Fig. 1). Further manipulation of the solution provides the additional simple relationships for $x \geq 0$:

$$x = \frac{5t^2 - 8t}{2} \text{ for } u = c \text{ in the backwash,}$$

(2a)

$$x = t^2 - t \text{ for } u = 0 \text{ (flow reversal).}$$

These curves delimit different characteristic regions of the swash flow, i.e. supercritical or subcritical flow, uprush or backwash (Fig. 1). Shen and Meyer (1963) and Peregrine and Williams (2001) is a particular solution for the swash flow. Of particular interest here is the prediction of only a small region of subcritical flow and a predominantly supercritical backwash. Indeed, close to the seaward end of the swash, $x \approx 0$, the backwash becomes supercritical prior to the time of maximum run-up. The supercritical nature of the backwash is of fundamental importance in the discussions later. While the largest swash events are typically forced by transient wave groups and consist of two or more uprushes in sequence (Baldock, 2006), the Peregrine and Williams (2001) solution is derived for a single swash event. It is thus not valid within the backwash bore or next incident bore, but this is outside the region of interest here, which is the time interval after bore collapse and before the next incident bore passes the point of interest. Friction can be expected to modify these results slightly, but the effects appear largely confined to the run-up tip (Packwood and Peregrine, 1981) and are not expected to significantly alter the flow characteristics indicated in Fig. 1, merely the exact value of the loci given by Eq. (2a and b).

The dimensional momentum (Navier–Stokes) equation in the $x$ direction (noting $x$ is now defined as horizontal) is

$$\rho \frac{D U}{Dt} = \rho X - \frac{\partial p}{\partial x} + \frac{\partial \tau_{xx}}{\partial x} + \frac{\partial \tau_{yx}}{\partial y} + \frac{\partial \tau_{zx}}{\partial z},$$

(3)

where $\rho$ is the fluid density, $U$ is the depth averaged horizontal flow velocity, $X$ is the body force, $p$ is the pressure, $\tau$ is the fluid shear stress, and $y$ and $z$ are the transverse and vertical directions, respectively. Neglecting transverse flow, the total acceleration, $DU/Dt$, is the sum of the local (Eulerian) acceleration, $\partial U/\partial t$, and the convective acceleration, $U \partial U/\partial x$. The body force, $X$, is zero in the $x$ direction in this instance; gravity acts through the pressure gradient, $\partial p/\partial x$. Shear stresses may reduce the acceleration of fluid particles, particularly close to the bed toward the end of the backwash when the flow becomes a fluid–sediment slurry (see Hughes, 1992; Raubenheimer et al., 2004), i.e., the flow velocity observed at a point is dependent on the cumulative effects of friction on the flow further upstream. However, in the following, only the relationship between the pressure gradient and the flow acceleration is considered, i.e. inviscid swash. Euler’s equation thus applies, which for hydrostatic pressure is (c.f. Dean and Dalrymple, 1991):

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

(4)

Fig. 1. Flow regions derived from the swash solution of Peregrine and Williams (2001). — — — — shoreline position, — $u = c$ (uprush), — — — $u = 0$, — — — $u = c$ (backwash).
and where $\eta$ is the water surface elevation with respect to an arbitrary horizontal datum. A positive pressure gradient, $\partial p/\partial x$ or $\partial q/\partial x$, corresponds to a water surface dipping downward in the negative (seaward or offshore) $x$-direction. The dimensional horizontal velocity, $U$, and bed parallel velocity, $u$, differ by a constant scaling factor (see Peregrine and Williams, 2001) and a factor $\cos \theta$, where $\theta$ is the bed slope. Since $1-\cos \theta$ is negligible for most natural and artificial beach slopes, $u$ and $U$ are effectively equivalent and the distance measured along the slope is equal to that in the horizontal (see Hibberd and Peregrine, 1979). Here Eq. (4) is used since it is more transparent than using a bed parallel coordinate system, and obtaining $\partial q/\partial x$ is straightforward with the measurement technique described in Section 3 below.

A fundamental assumption in this analysis is that the pressure within the swash flow is hydrostatic. The assumption of hydrostatic pressure in shallow free surface flows with minimal streamline curvature has been conventional in the literature for over 100 years. Since 1871, the Saint-Venant equations and their derivatives, particularly the non-linear shallow water equations, have been shown to accurately describe the essential properties of a very large class of free surface flows with and without friction, ranging from dam break flows (Ritter, 1892; Whitham, 1955) to non-breaking wave swash (Carrier and Greenspan, 1958), the propagation of bores (Stoker, 1957), bore-driven swash (Shen and Meyer, 1963; Peregrine and Williams, 2001), one-dimensional waves in channels (Lighthill, 1978) and tsunami run-up (Carrier et al., 2003). Similarly, numerical models based on the hydrostatic assumption describe the essential features of the flow in the surf and swash zones with a good degree of accuracy (e.g. Hibberd and Peregrine, 1979; Kobayashi et al. 1989; Watson and Peregrine, 1992; Raubenheimer et al., 1995; Raubenheimer, 2002; and many others). We are not aware of any data that directly demonstrates swash flows are hydrostatic or otherwise. However, recent laboratory measurements (Petti and Longo, 2001; Cowen et al., 2003) showing that the velocity field is always primarily parallel to the bed suggests that the assumption is a practical one. Furthermore, friction effects are usually small and expected to predominantly influence the shape of the leading edge (e.g. Whitham, 1955; Hogg and Pritchard, 2004). This is discussed further below with reference to the field observations. Highly turbulent flow flows down steep spillways at very high Reynolds numbers ($>10^8$) or within turbulent boundary layers are assumed to still obey the hydrostatic law (e.g. Henderson, 1966; Stansby, 2003), at least over length scales of order of the flow depth. While the fluid density may change in regions of high air concentration, we are unaware of any data that indicates that this is likely to change the relationship between the free surface slope and the pressure gradient in the fluid. Therefore, in the following, we assume that the surface slope is a good direct measure of the horizontal pressure gradient within the main body of the flow.

Some additional relationships describing the flow accelerations can be derived from the Peregrine and Williams (2001) swash solution, where all variables are again non-dimensional as in their paper:

\[
\frac{\partial u}{\partial t} = -\frac{2}{3}\frac{q}{t^2} \left( t^2 + x \right), \tag{5}
\]

\[
\frac{\partial u}{\partial x} = \frac{2}{3}\frac{q}{t}, \tag{6}
\]

\[
\frac{d}{dt}\left( \frac{u}{t} \right) = \frac{4}{9q} \left( t^2 + x \right), \tag{7}
\]

\[
x = t^2 - t \quad \text{for} \quad \frac{\partial u}{\partial x} = 0 \tag{8}
\]

and following Pritchard and Hogg (2005),

\[
x = 2t - 5t^2 \quad \text{for} \quad \frac{D u}{D t} = 0. \tag{9}
\]

Shoreward of the point of bore collapse, $x > 0$, Eq. (5) gives a negative (offshore) local acceleration at all times. The horizontal flow is also diverging at all times (Eq. (6)), leading to rapid thinning of the swash (Hibberd and Peregrine, 1979; Larson and Sunamura, 1993; Raubenheimer and Guza, 1996). Shoreward directed convective acceleration (Eq. (7)) and total acceleration (Eq. (9)) occur close to the time of bore collapse as noted by Yeh et al. (1989) and Hughes and Baldock (2004), although the solution may not be valid close to the singularity at $x = t = 0$ (Peregrine and Williams, 2001). Fig. 2 illustrates the regions of shoreward and seaward accelerations in the $x$–$t$ plane. It is interesting to note that since $\partial u/\partial x$ is always positive, the direction of the convective acceleration (Eq. (8)) is always the same as the flow direction, in contrast to steady wave motion. Furthermore, the convective acceleration and local acceleration counterbalance each other during the uprush, resulting in negative total acceleration for nearly the whole swash event.
From Euler’s equation (Eq. (4)), the horizontal pressure gradient is expected to be negative (giving a landward net pressure force) for only approximately 10% of the swash cycle, and then only in the region close to the point of bore collapse. This is consistent with the data of Baldock and Holmes (1997, 1999), Petti and Longo (2001) and the estimates of Hughes and Baldock (2004). Therefore, for most of the rundown and the entire backwash the Peregrine and Williams solution gives a seaward dipping water surface. These results are in marked contrast with the estimates of local accelerations and horizontal pressure gradients inferred from Eulerian velocity and depth measurements by Puleo et al. (2003).

Puleo et al. (2003) presented data from the upper swash that they interpreted as showing large shoreward directed local flow accelerations and horizontal pressure gradients at the start and end of the swash cycle, an idea originally presented by Puleo and Holland (2001). The horizontal pressure gradient was stated to be onshore (corresponding to a shoreward dipping water surface) during the entire swash cycle. Hence, the mean inferred pressure gradient for that data must also be negative, corresponding to a mean water surface dipping in the landward direction. This is inconsistent with the widespread observation that the mean water surface in the inner surf and swash always dips seaward, i.e. wave setup (Bowen et al., 1968, Longuet-Higgins, 1983; Nielsen, 1988). Puleo and Holland (2001) and Puleo et al. (2003) also argued that the backwash was opposed or decelerated by an adverse pressure gradient arising from the fluid mass on the lower beach, or the next incident bore further offshore. This is difficult to reconcile with a backwash surface dipping seaward in the same way as the beach slope (as opposed to deeper water depths further offshore). Furthermore, the backwash is nearly always a supercritical flow (Fig. 1), a condition readily determined from the flow depth and flow velocity (e.g. Hughes et al., 1997b) or careful visual observation (see Section 4).

A fundamental tenet of “open channel” or free-surface hydraulics is that supercritical flow is not influenced by the downstream flow conditions unless those conditions propagate upstream to, or occur at, the point of interest or measurement location (e.g. Daugherty and Franzini, 1965; Chanson, 2004). Typical examples are hydraulic jumps and fully developed bores; in neither case does the horizontal pressure gradient influence the flow upstream of the leading edge of the jump or bore. Therefore, deceleration of a supercritical backwash by an adverse pressure gradient further downstream is contrary to basic principles. Furthermore, if an incident bore is fully developed, i.e. a positive surge or shock, then it will have no influence on the upstream flow, even if that flow is subcritical. These conditions are analogous to a tidal bore propagating upstream, or a dam break into still water (e.g. Chanson, 2004). Hence, neither subcritical nor supercritical uprush/backwash flows will be influenced by subsequent fully developed incident bores until the bore reaches the measurement location.

The horizontal forces on sediment particles arise from pressure gradients and drag forces (Nielsen, 1992, p. 98.). The pressure gradient force may be written in terms of total acceleration as in Eq. (4), but the local acceleration is frequently used in conjunction with an inertia or hydrodynamic mass coefficient instead, since ∂u/∂t is “easier” to measure with a current meter. If the particle is also accelerating, the inertial force on the particle may be better described by using the slip velocity (Nielsen, 1992, p. 167). The pressure force from the body of the flow is unchanged. Hence, in a modified transport model of the form q = ut+ f(Du/Dt), the direction of the pressure gradient or flow acceleration is particularly important. For example, incorporating a pressure gradient or flow acceleration term acting in the wrong direction into a sediment transport model of the form above potentially leads to large errors, particularly as u→0, i.e. transport in the wrong direction. Accounting for a pressure gradient acting in the wrong direction may also lead to misleading results when considering the effects of friction on the shoreline motion. Consequently, given the significant differences between the flow accelerations and pressure...
gradients predicted by the analytical swash solution and previous work and those inferred by Puleo et al. (2003), direct measurements of the water surface slopes and pressure gradients in the swash on natural beaches appear to be beneficial and these are reported below.

3. Field study

3.1. Methodology

A novel but simple technique was developed to resolve instantaneous and spatial mean water surface slopes (Fig. 3). In its simplest form a physical horizontal datum is set up on the beach by means of a taught stringline extending seaward from the beach face. The ends of the stringline can be levelled to within ±1 mm over a distance of 5–20 m using conventional surveying techniques or a manometer tube. If the seaward end of the stringline is exposed but covered further landward, then the water surface is dipping seaward, and vice versa. Visual observation, still photography or video photography is then sufficient to determine the direction of the instantaneous water surface slope and direction of the pressure gradient in the swash. The mean slope between two points can also be determined from digitised data.

In the field a series of 5 horizontal stringlines were stacked vertically at 5 cm intervals, although any number and spacing could be used as required. Each stringline was 3 mm diameter orange cord, easily visualised in photographs or video records under a range of lighting and surf conditions. Thin (5 mm diameter) vertical rods were spaced along the stringlines to provide a horizontal reference scale in photographs, with the stringline spacing providing a vertical scale. Image rectification is therefore not required and no particular camera orientation is necessary; best results are obtained looking long-shore, but in high energy swash photographs may be taken at an angle from further shoreward. There is no requirement to maintain the camera axis horizontal unless horizontal lines are desired in the image. The vertical rods assist in defining the water surface at locations where the surface is below or between the stringlines. The rods also enable the speed of an incident bore or swash front to be determined from video records. In the present study the stringline spacers were placed at 5 m intervals, with vertical rods at 1–2 m intervals. The total length of the stringlines varied from 20 m for mild beach gradients to 5 m for steep beach gradients. Fig. 3(b) and photographs in Section 4 illustrate the complete arrangement.

The method enables the instantaneous water surface to be determined to within ±3 mm at cross-shore locations separated by 5 m or more, resolving the mean gradient to within ±0.001, or 1/20th–1/100th of typical beach gradients. In addition, the water surface slope can be determined exactly to be either seaward or landward where the water surface cuts a stringline—thus at these points no averaging over the horizontal is required. The technique is also applicable in the inner surf zone and provides information on the steepness of the front face of incident bores, together with the water surface slope either side of the bore. The stringlines can also be sunk within a trench so that they exit the beach at different elevations. This enables an accurate assessment of the water surface slope at the uprush tip, allows for bed level changes, and is necessary on steep beaches since the stringlines rapidly reach a considerable elevation above the
The lines may also be stepped down the beach to account for tidal water level variations. Numerical values of the surface elevation relative to any stringline and fixed horizontal coordinate are easily extracted from the images with standard image analysis software or from hard copies. Water surface elevations can be obtained with an accuracy better than the stringline thickness (3 mm) where the surface cuts the line and to with an accuracy of better than 5 mm where the vertical rods intersect the surface. Horizontal coordinates are accurate to within 1–2 cm. Over shorter distance of order 1 m, the surface gradient can thus be obtained to within ±0.01. Bubbles and splashes can obscure the “true” water surface at certain points, but do not hinder determining overall mean surface slopes. Multiple images are available to overcome this if necessary. It is not necessary to determine the surface positions at locations other than where the surface intersects a line or vertical rod, but the images show the overall surface slope very clearly, even at the small scale presented here.

3.2. Field sites

Field observations were made at four sites on the Australian east coast: Ocean Beach, Umina, New South Wales (NSW); Avoca Beach, NSW; Belongil Beach, NSW and Eagers Beach, Moreton Is., Queensland. The field deployments encompass the period June–December 2004, with the data presented here collected over 9 different days. For these beaches, the beach gradient in the swash zone varied between 0.028 and 0.11 (Table 1). Surf zone beach profile gradients ranged from 0.025 to 0.04. Sediment sizes varied between 0.22 and 0.53 mm. Offshore significant wave height over the different deployments and measurement times ranged from 0.98 to 1.9 m, with peak wave periods between 6.2 and 12.2 s. The surf similarity parameter (Battjes, 1974, based on offshore significant wave height and surf zone gradient) ranged from 0.11 to 0.62, indicative of both spilling and plunging breakers. On the steeper beaches shore breaks frequently occurred at high tide.

The stringlines were deployed on both rising and falling tides, with observations made from the inner surf zone, through bore collapse and to the run-up tip on all beaches. Data are obtained from either photographic or video records. The findings discussed in Section 4 are based on over 1000 digital photographs and over 3 h of video record, part of the latter digitised to give individual images at 0.2 s intervals. In the upper swash, where the swash front was moving relatively slowly, visual observation was sufficient to determine a landward or seaward dipping water surface slope.

4. Results

The results are best described by photographs illustrated in Figs. 4 and 5. These photographs were selected on the basis of image quality as much as for the flow conditions they depict, and therefore are from still photographs. Although space limits the number of images that can be presented here, the images shown are representative of the entire set of observations. Note that in panels 4(a), (b) and 5(a) the vertical rods were not equally spaced as they were placed initially to assist in highlighting the water surface, rather than to provide a reference scale. All stringlines were horizontal, even if they do not appear so in the images. While black and white images are shown in the printed version of the journal, colour versions with improved clarity are given in the electronic version (i.e. ScienceDirect).

Panel 4(a) illustrates the water surface slope at the commencement of collapse of a fully developed bore. It is of interest to note that the water surface slope behind the bore is very close to horizontal, suggesting that in the inner surf zone significant total fluid acceleration is confined to the bore front (see also panels 4(e) and 4(f)). This is important in the context of sediment suspension and transport just prior to bore collapse. The red arrows highlight short exposed lengths of the same stringline, illustrating that the technique can provide a very accurate measure of the instantaneous free surface profile over large distances.

Panels 4(b–e) show backwash flows at the seaward end of the swash zone, together with the next incident bore. In panels 4(b), (d) and (e) the backwash is supercritical, whereas in panel 4(c) it is subcritical. Supercritical flow can be
identified by the fact that the vertical rods and star posts do not cause an upstream flow disturbance, i.e. small disturbances cannot propagate upstream.

In all cases, including the subcritical backwash, the water surface clearly dips seaward to the leading edge of the next incident bore, i.e. the pressure
gradient is positive and the total acceleration negative. Observations at times of flow reversal show that the incident bore similarly has no influence on almost stationary upstream flow. These results are consistent with the analytical swash solution and the basic characteristics of supercritical flow and shocks as discussed previously. At the end of the backwash the water surface slope approaches...
the beach slope and remains seaward dipping until the water drains away or the arrival of the next incident bore. Panel 4(f) shows more detail during bore collapse; the water surface behind the bore front is again close to horizontal, with the shoreward dipping water surface limited to the leading edge (first 0.5–1 m). It is also clear from this image that pressure sensors are unlikely to give an accurate measure of the surface gradient as a result of the intense turbulence and air entrainment. While the assumption of hydrostatic pressure may be violated in turbulence and air entrainment. Figs. 4 (a and f) suggest the pressure gradient behind the bore front is very small. Strong surface gradients occur across the bore front as expected, but these have no influence on the backwash further up slope.

The water surface slopes and pressure gradients during uprush are illustrated in panels 5(a–f). The leading edge of the uprush is convex as noted by Baldock and Holmes (1997), rather than concave as given by the inviscid swash solution. This results in a very small region of order 0.5 m behind the leading edge where shoreward slopes occur, and this is discussed in more detail below. In this region of the flow the depth is typically less than 5–10 cm and the flow exhibits the usual “frothy” nature at the tip. Close to the point of bore collapse, the shoreward dipping slopes at the leading edge correspond to maximum negative pressure gradients of order $-0.05–0.1$ (Fig. 6). In contrast, in the middle and upper swash zone the water surface slope even at the leading edge is frequently horizontal or seaward dipping (panels 5 (c and f)). Seaward of the leading edge the water surface oscillates about the horizontal due to small irregularities (see Fig. 6) or dips seaward for the remainder of the swash event. This is also the case in the lower swash.

Fig. 6 shows the above results in graphical form, where both the surface elevation and surface gradient have been derived directly from the images. Positive gradients correspond to a seaward dipping surface. The data are shown at points where the surface intersects a stringline or vertical rod. While resolution could clearly be improved with more lines and/or rods, it is more than adequate for the purpose of determining the surface slopes. During backwash, (Fig. 6(a)), the surface slope increases seaward, approaching the beach gradient toward the latter stages. The slope is positive until the toe of the incident bore. After bore collapse, in the lower swash the surface slope behind the leading edge is almost zero, with small deviations due to residual turbulence and secondary waves on the surface (Fig. 6(b and d)). The leading edge dips shoreward over a distance of about 0.5 m with a gradient of about $-0.15$. Friction leads to a convex or rounded front, and from Whitham (1955), infinite negative gradients could occur at the intersection of the water and beach face. In this region the pressure gradient balances friction. For the dam break solutions, the maximum velocity occurs at the tip and $\partial u/\partial t$ and $DU/Dt$ are zero or negative to leading order behind the front (Whitham, 1955; Hogg and Pritchard, 2004). On steeper beaches, or in the mid-upper swash on milder slope beaches, the surface may dip seaward even at the leading edge (Fig. 6(c)). The different shape of the swash tip during uprush and backwash may be relevant to improving ballistic swash models that incorporate friction at the tip (e.g. Hughes, 1995; Puleo and Holland, 2001).

Recent analytical solutions, as well as equilibrium type sediment transport models, suggest that suspended sediment concentrations (SSC) for fine-medium sands are maximum very close to the swash tip during uprush (e.g. Pritchard and Hogg, 2005), since that is where the flow velocity is greatest. However, the predicted sediment flux peaks some way behind the front as a result of limited flow depths in the tip region. Field data suggests the SSC peaks further somewhat further behind the tip, of order 0.5–2 s (e.g. Osborne and Rooker, 1999; Puleo et al., 2003), but this may be partly related to instrument elevation and OBS response in the “frothy” tip. Hence, the importance of the convex front in terms of sediment transport remains to be assessed, particularly relative to the contribution from pre-suspended sediment in the bore (Jackson et al., 2004; Pritchard and Hogg, 2005; Alsina et al., 2005). Behind the leading edge, the instantaneous surface gradient oscillates around zero in the lower-mid swash, increasing to order $\beta/2$ near the run-up tip on the steeper beaches. Indeed, of interest is how frequently the surface is nearly horizontal over distances of up to 5 m, both behind the bore front (Fig. 4(a)), and in the swash (Fig. 5(a)), and particularly on the milder sloping beaches. The surface gradient in the backwash ranges from order $\beta/2$ to $\beta$. These limits are physically sensible and consistent with previous analytical and numerical results (Hibberd and Peregrine, 1979; Peregrine and Williams, 2001) and small-scale experimental data (Baldock and Holmes, 1997). In the backwash, we have never observed the exact surface slope where
Fig. 6. Cross-shore variation in instantaneous free surface elevation and free surface gradient. —◇—, surface elevation; —□—, surface gradient (rhs). (a) Supercritical backwash flow, Belongil beach (panel 4(b)). Most negative x location corresponds to the toe of the incident bore. (b) Uprush, lower swash, Belongil Beach (panel 5(a)). (c) Uprush, mid-upper swash, Ocean Beach (panel 5(c)). (d) Uprush, mid-lower swash, Eagers Beach (panel 5(e)).
the line cuts the surface to be negative, except during the formation of backwash shear waves (e.g. Peregrine, 1974).

With the exception of the blunt or convex leading edge, the present observations clearly show the near-surface horizontal pressure gradient within the swash to be zero or positive everywhere at all times. Hence, noting the caveats discussed above, from Eq. (4), for all practical purposes, the total acceleration in the swash zone is therefore negative or offshore at all times. Again assuming hydrostatic pressure, the observations show that at any fixed point the boundary layer is predominantly subjected to an adverse pressure gradient during the uprush. In contrast, during the backwash the boundary layer is always subjected to a favourable pressure gradient until the water drains away or the next incident bore arrives at that location. These results have significant implications for sediment transport modelling in the inner surf and swash, since new models now incorporate pressure gradient or acceleration terms directly (e.g. Teakle and Nielsen, 2003; Hsu and Hanes, 2004). The pressure gradients are also relevant for calculating forces on immersed bodies during long wave runup, where the inertia force is again proportional to the pressure gradient, not necessarily the local acceleration. Finally, the influence of the adverse and favourable pressure gradients on the boundary layer during uprush and backwash, respectively, may counter any effects of infiltration or exfiltration on the boundary layer, although it must be noted that near the swash front the boundary layer is highly non-uniform.

5. Conclusions

Field observations of instantaneous water surface slopes in the swash zone have been presented, and these are likely a very close approximation to the horizontal pressure gradient. Observations were made using a simple but novel technique, from which the water surface slope can be determined exactly to be either seaward or shoreward dipping at certain locations. The method also provides data on the instantaneous mean surface slope over distances from 1 to 10 m. Further, it may also be used to determine the water surface slopes either side of inner surf zone bores, together with the shape of the bore roller and the instantaneous depth profile of the swash lens. Large-scale studies of dam break free-surface profiles is another potential use of the technique.

Close to the location of bore collapse, shoreward dipping water surface slopes (typically $-0.05$ to $-0.1$) occur over a small region (order 1–0.5 m) at the convex leading edge. In the middle and upper swash, the water surface slope at even the leading edge is frequently horizontal or seaward dipping. Behind the leading edge region the water surface slope was observed to be horizontal or seaward dipping at all times throughout the swash uprush. The water surface slope during the backwash was observed to be always dipping seaward, approaching the beach slope, and remained seaward dipping until a new uprush edge or incident bore passed any particular cross-shore location of interest.

The analytical swash solution is further illustrated by some simple relationships describing the different flow characteristics of the swash and regions of different flow acceleration in the $x$–$t$ plane and these are consistent with the present observations. Finally, the observations show that the total fluid acceleration is predominantly negative or offshore throughout the swash. The swash boundary layer is therefore subject to a weak adverse pressure gradient during uprush and a stronger favourable pressure gradient during the backwash. These gradients may counter any influence from infiltration and exfiltration on the swash boundary layer. The observations have significant implications for sediment transport modelling.

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