Swash-zone morphodynamics

Gerhard Masselink\textsuperscript{a,*}, Jack A. Puleo\textsuperscript{b}

\textsuperscript{a}School of Geography, University of Plymouth, Drake Circus, Plymouth PL4 8AA, UK
\textsuperscript{b}Department of Civil and Environmental Engineering, Center for Applied Coastal Research, Ocean Engineering Building, University of Delaware, Newark, DE 19716, USA

Available online 31 March 2006

Abstract

Hydrodynamic forcing with respect to sediment transport and morphologic change, paying particular attention to relevant swash asymmetries, is reviewed. The hydrodynamics are categorized into their individual effects: high- and low-frequency motions, bores and turbulence, in/exfiltration, shear stresses and friction coefficients. Individual effects are then related to their potential for driving or influencing sediment transport and morphological change. Additional concepts such as settling/scour lag and sediment advection that have largely been ignored are also discussed. A simple framework is presented for the morphological response of the beachface under swash zone hydrodynamic processes. The framework acknowledges that the beachface cannot be considered in isolation from the surf zone and that the two zones are strongly linked through feedback processes. The swash zone itself is also a morphodynamic system and morphological response occurs as a result of disequilibrium between the beachface gradient and asymmetries in the swash hydrodynamics. Any beachface morphological development in response to such equilibrium will have direct and indirect effects on swash hydrodynamics and sediment transport processes. It is concluded that the two issues requiring most urgent research attention with regards to swash zone sediment transport processes are the roles of sediment advection and longshore swash motion.

© 2006 Elsevier Ltd. All rights reserved.

Keywords: Swash zone; Wave runup; Bores; Beaches; Sediment transport; Morphodynamics

Contents

1. Introduction .......................................................... 662
2. Surf zone forcing and swash hydrodynamics .......................... 663
   2.1. Some key characteristics of swash motion ......................... 663
   2.2. High- and low-frequency swash motion .......................... 665
   2.3. Bores and turbulence ......................................... 665
   2.4. Cross-shore swash flows ....................................... 666
   2.5. Shear stresses and friction coefficients .......................... 667
3. Swash zone sediment transport ........................................ 668
   3.1. Field measurements of swash zone sediment transport .................. 668

*Corresponding author. Tel.: +44 1752 233 050; fax: +44 1752 233 054.
E-mail addresses: gmasselink@plymouth.ac.uk (G. Masselink), jpuleo@coastal.udel.edu (J.A. Puleo).
1. Introduction

The swash zone is that part of the beach alternately covered and exposed by uprush and backwash. The time scale of swash motion is highly variable and ranges from seconds on calm, steep and reflective beaches (e.g., Hughes et al., 1997a), to minutes on energetic, low-gradient and dissipative beaches (e.g., Butt and Russell, 1999). The swash zone is characterised by strong and unsteady flows, high turbulence levels, large sediment transport rates and rapid morphological change (Puleo et al., 2000), and represents arguably the most dynamic region of the nearshore. The morphological equivalent of the swash zone is the beachface, which is the relatively steep section of the beach profile extending seaward from the berm to the low tide level. The beachface is clearly defined on low-tidal beaches where it forms a single, relatively steep morphological unit dominated by swash processes. It is less obvious on high-tidal beaches where the increased tidal excursion exposes the beachface to a mixture of swash, surf and shoaling wave processes, resulting in a considerable reduction of the gradient (Masselink and Turner, 1999).

There is the perception that the swash zone is a notoriously difficult location to undertake morphodynamic research (Hughes and Turner, 1999) and that it is one of the most scientifically challenging oceanic environments for describing sediment transport (Puleo et al., 2003). The shallow, aerated, turbulent and rapidly varying swash flow certainly provides a challenge for even the most advanced and robust hydrodynamic equipment. Obtaining reliable instantaneous sediment transport rates is even more problematic, not only because of the large magnitude of the sediment fluxes (Masselink and Hughes, 1998), but also due to the various modes of transport involved, including bed load and suspended load, sheet flow and even single-phase flow at the end of the backwash (Hughes et al., 1997b). Analysis of swash zone data is further impeded by its intermittent nature, precluding the application of conventional time series analysis techniques such as spectral analysis, and making critical comparisons between theory and observations difficult (Hughes and Baldock, 2004). On the other hand, the swash zone is much more accessible than the rest of the nearshore zone. Instruments can be deployed, maintained and serviced with relative ease and, most importantly, morphological measurements can be conducted with high precision and resolution. Only during the last decade or so have coastal researchers come to the realisation that the swash zone is indeed measurable and this renewed interest has led to a spate of field investigations, the results of which are discussed in two recent reviews (Butt and Russell, 2000; Elfrink and Baldock, 2002).

Swash zone sediment transport processes are important to society for two main reasons. Firstly, the water motion within the swash zone provides the principal mechanism for cross-shore sediment exchange between the subaerial and sub-aqueous zones of the beach (Masselink and Hughes, 1998). Offshore and onshore sediment transport in the swash zone, therefore, contributes significantly to shoreline accretion and erosion. Secondly, a significant part of the longshore sediment transport occurs in the swash zone and may account for a large portion of the total littoral drift (e.g., Bodge and Dean, 1987; Kamphuis, 1991; Smith et al., 2003), especially on steep (reflective) beaches (Van Wellen et al., 2000). Swash processes are also of great interest academically and a particularly pertinent research question is: Why are some beaches steep and others shallow? The steepness of the beachface has been ascribed to the pronounced onshore asymmetry in the swash flow (Bagnold, 1940) and it is generally assumed that an equilibrium beachface gradient can be defined, reflecting a balance between swash asymmetry and the downslope component of gravity (Hardisty, 1986). Closely aligned with this notion of equilibrium is the formation of beach cusps, which are thought to evolve as a result of mutual adjustment between
beachface morphology and swash asymmetry (Werner and Fink, 1993; Coco et al., 2000).

Our approach is to consider the swash zone and beachface part of a mutually interacting and co-evolving morphodynamic system (Cowell and Thom, 1994), comprising swash zone hydrodynamics, groundwater dynamics, sediment transport and beachface morphology (Fig. 1). Importantly, this system does not exist on its own, but interacts with the surf zone morphodynamic system and the terrestrial water table. Both systems are ultimately forced by the offshore incident-wave conditions and the ocean tides, and a very important environmental control is exerted by the sediment characteristics, mainly through the size and the sorting of the beach sediments. The surf zone and swash zone morphodynamic systems are linked through feedback processes, but the connection from surf to swash is more significant than the other way around.

The objective of this paper is to provide an overview of the hydro- and sediment dynamic processes and ensuing morphological change in the swash zone of natural sandy beaches. At the outset, it should be made clear that our focus is on cross-shore processes — the role of longshore swash flows and the development of three-dimensional beachface morphology are therefore not addressed. We neither focus on the spectral structure of the runup motion, the stochastic prediction of maximum runup or detailed theories for swash hydrodynamics. Section 2 discusses the surf zone forcing of swash processes and describes some of the key hydrodynamic characteristics of swash motion.

Section 3 reviews previous field studies of swash zone sediment transport and further looks at the factors affecting swash zone sediment transport, with specific emphasis on swash asymmetry. Section 4 addresses the morphological response of the swash zone and discusses the feedback between beachface morphology and swash hydrodynamics. Section 5 provides the conclusions and some perspectives for future work.

2. Surf zone forcing and swash hydrodynamics

2.1. Some key characteristics of swash motion

There is no precise definition of the seaward edge of the swash zone, although it has been suggested that the seaward edge of the swash starts where bore turbulence begins to significantly affect the sea bed (Puleo et al., 2000). Most researchers, however, reference the swash zone as either the region of the beach profile where there is intermittent fluid coverage, or the time-varying region extending from the point of bore collapse on the beachface to the maximum uprush limit (Hughes and Turner, 1999). Adopting the latter definition, Fig. 2 shows an idealized time history of swash motion for a monochromatic wave train on a planar-sloping permeable beach. The example shown assumes a sandy beach on a rising tide with a low ground water level. Initially, a bore is approaching the point of fluid intersection with the foreshore and a sensing device, such as a current meter, may be just out of the fluid domain leading to discontinuous measure-
ments. High onshore-directed fluid velocities are associated with the bore in the upper portion of the water column, whereas strong offshore-directed flows occur near the bed. The turbulence associated with the bore and the water column shear are responsible for high vertical mixing. After the bore has collapsed at the beachface, as shown in the next panel, the resulting uprush motion may briefly accelerate in the shoreward direction as a result of the pressure push of the collapse itself. During uprush, the fluid velocities are all onshore and, depending on the permeability and moisture content of the beach sediment, some of the uprush fluid may infiltrate the foreshore surface. By the third panel, the uprush has reached its maximum landward extent and by this time the flow in the lower swash region has already started to head offshore as backwash, resulting in the thinning of the swash lens. At this time, the flow accelerates downslope and fluid may still be infiltrating the beach. Finally, the seaward portion of the backwash begins to interact/collide with the next bore, causing the seaward swash flow to decelerate. Meanwhile, further shoreward, a retrogressive bore may develop and fluid may be exfiltrating. Clearly, the direction of through-bed flow is dependent on grain size and groundwater levels and hence the directions and relative magnitudes shown in Fig. 2 may be typical only of the conditions assumed in the schematic.

Time series of hydrodynamic data collected in the swash zone are discontinuous and basic concepts that have meaning in the surf zone and beyond, such as wave height, length and period, have no simple mapping into the swash zone. For example, one may define the beginning of the uprush occurring as the instant the bore reaches the time-varying shoreline location, and the end of the backwash as the instant just before the next uprush begins. While these notions make sense conceptually, the time between these occurrences is not as constant as, say, the peak period measured offshore, due to interactions of the natural wave field and swash motions. Hence, the observed swash period, or, more correctly, the swash duration, cannot be assumed representative for a series of swash motions on a natural beach. In fact, the swash zone acts as a low-pass filter, removing high-frequency motions due to these interactions (Emery and Gale, 1951; Sonu et al., 1974; Mase, 1988). Because the swash duration varies over time, a wide range of swash excursion distances is also expected. There are also profound theoretical differences between

Fig. 2. Schematic of swash cycle. Thick solid curve is the foreshore surface. Thin solid curve is the water surface. Black dashed curve is the water table elevation. Grey dashed curve is the water table level due to runup (schematic is more appropriate to a sandy beach on a rising tide). Solid circle represents location where an in-situ sensing device may be placed. Arrows indicate flow direction and relative magnitudes (after Osborne and Rooker, 1997).
the water motion in the swash and surf zone: after bore collapse at the bottom of the swash zone, the resulting fluid motion becomes a thin sheet of run-up (Shen and Meyer, 1963), and has been likened to a rarefaction wave (Freeman and Le Méhauté, 1964; Miller, 1968) that no longer exhibits the characteristics of a combined longitudinal/transverse wave or shock wave (bore) observed in the surf zone. Hence, the concept of water particles having an orbital trajectory is no longer applicable to swash flows.

Based on Fig. 2 it is also apparent that in situ measurements made with a current meter, pressure sensor or sediment sensing device will be subjected to intermittent emergence from the water column if they are placed in the swash zone. Not only does this intermittency affect statistical analysis procedures (Hughes and Baldock, 2004), but it may complicate understanding of the swash processes, because the sampling occurs in an Eulerian frame of reference, whereas the swash motion itself is distinctly Lagrangian. It is very difficult, however, to measure the Lagrangian motion of individual fluid parcels and our current understanding of swash hydrodynamics is still largely based on Eulerian flow measurements.

2.2. High- and low-frequency swash motion

There are generally two approaches to describing swash motions on natural beaches (Baldock et al., 1997); (1) swash flows resulting from the collapse of high-frequency bores \( f > 0.05 \text{ Hz} \) on the beachface; and (2) swash flows characterised by standing, low-frequency \( f < 0.05 \text{ Hz} \) motions (see Butt et al., 2005, for time series displaying these differences). Which type of swash motion is prevalent depends on the incident-wave conditions and the beach morphology, and can be predicted using the surf similarity parameter \( e_b \) (Guza and Inman, 1975)

\[
e_b = \frac{4\pi^2 H_b}{2gT^2\tan^2 \beta},
\]

where \( H_b \) is the breaker height, \( g \) is gravity, \( T \) is the incident-wave period and \( \tan \beta \) is the beach gradient. Values of \( e_b > 20 \) indicate dissipative conditions (swash characterised by standing long-wave motion), whereas \( e_b < 2.5 \) indicate reflective conditions (swash dominated by incident-wave bores) (Wright and Short, 1984).

The morphodynamic taxonomy with its reflective and dissipative end members provides a useful first-order framework for discussing swash processes, but disregards the transfers of energy from high- to low frequencies that commonly occur on natural beaches (Mase, 1988). A more realistic consideration of the different frequency components in the surf and swash zones is therefore depicted in Fig. 3, which compares the incoming wave energy with that observed at the shoreline. In the simplest case, monochromatic waves shoal and break in the surf zone and drive swash oscillations at a frequency similar to the incident frequency. Note, however, that this case does not occur for natural swash, as monochromatic wave fields are only approachable in a laboratory setting (although ‘clean’ swell waves on a steep beach may come close). In the random wave case, both short and long (free and bound) waves affect swash oscillations. Incident short waves can contribute to both the high- and low-frequency oscillations, where the latter can be driven by wave groups (Baldock and Holmes, 1999; Shah and Kamphuis, 1996), uprush/backwash interactions (Carlson, 1984; Erikson et al., 2005) and bore overtaking/capture (Bradshaw, 1982). Incident long wave motions are generally manifested as shoreline reflections and observed as a standing wave component to the low-frequency swash signal (Huntley, 1976; Suhayda, 1974). Most swash hydrodynamic research has been conducted into bore-driven swash, and only little research effort has addressed swash on ultra-dissipative beaches where the swash may most closely resemble that of a standing wave.

2.3. Bores and turbulence

The highest frequency motions in the swash zone occur as turbulence generated at the bed by frictional processes and, more readily, by the churning of water in the leading edge of swash and bore motion. The landward propagation of bores and the associated collapse at the beachface represent the advection of turbulence, and also of sediment, into the swash zone. Sediment, and to a lesser extent, turbulence, can also be advected from the swash zone back into the surf zone, for example, in relation to hydraulic jumps that may develop at the bottom of the swash zone.

The most detailed measurements of turbulence in the swash zone and inner surf zone are available from laboratory experiments. Yeh et al. (1989) observed bore collapse in a flume and showed that the highly three-dimensional turbulence generated
near the shoreline is advected shoreward with the bore front, spreads downward toward the bed (Madsen and Svendsen, 1983; Svendsen and Madsen, 1984). Recent laboratory studies have further extended our knowledge of turbulence in the swash zone and have demonstrated that: (1) turbulent energy flux is shore-directed; (2) uprush turbulence is dominated by bore-generated and bore-advected turbulence which evolves analogous to grid turbulence; (3) backwash turbulence is dominated by the growing boundary layer and compares well to the classic flat plate boundary theory near the bed; and (4) the Kolmogorov length scale increases towards the bed indicating that, during uprush, dissipation is less important near the bottom than near the surface (Cowen et al., 2003; Petti and Longo, 2001a, b).

Field studies of turbulence levels in the swash zone are rare and have been limited to the transition between swash and surf zone. Flick and George (1990) measured high-frequency swash motions using hot film probes and found that the turbulence length scales depend on the bore height and local depth, but may decrease sharply under the bore itself. Osborne and Rooker (1999) used an acoustic Doppler velocimeter (ADV) to show that the turbulent kinetic energy is large and nearly equal during uprush and backwash. In contrast, Butt et al. (2004), also using an ADV, found high levels of turbulence associated with the bore front that were largest during the backwash/uprush transition. Furthermore, the highest values of turbulent kinetic energy estimates occurred while the near-bed velocity was still offshore-directed, in line with the idea of the surface-generated turbulence penetrating towards the bed (see Longo et al., 2002 for further details on turbulence measurements and characteristics in the swash zone).

2.4. Cross-shore swash flows

Field measurements of the flow field within the swash zone during uprush and backwash have been made using a variety of methods, but individual studies have repeatedly shown some general features of the swash zone internal flows and highlight the significant differences between uprush and backwash. Uprush flows are typically originated by the collapsing bore, especially on steep beaches, and may have a history through collision with the preceding backwash (Hibberd and Peregrine, 1979; Jensen et al., 2003). The collision between a powerful backwash and a proceeding bore can result in a nearly stationary bore or hydraulic jump (Brenninkmeyer, 1976; Butt et al., 2002; Nelson and Miller, 1974), where the incoming bore is roughly held in place by the rapidly accelerating offshore flows, or

Fig. 3. Schematic showing transfer of offshore energy into swash zone oscillations (after Mase, 1995).
results in a slight bore retreat. The uprush/backwash collision may also create backwash vortices that are efficient suspension mechanisms and may be responsible for the formation of beach steps (Bauer and Allen, 1995; Matsunaga and Honji, 1980; Miller and Zeigler, 1958). Note that these two opposing flows are also likely to generate strong mid-water column shear (Cowen et al., 2003) that may complicate advection-based sediment transport models using a single current meter, because the transport could occur in both the offshore and onshore directions simultaneously depending on elevation (Butt et al., 2004). After the initiation of uprush motion, turbulence likely acts to homogenize much of the water column such that the flow at the bottom of the swash zone may be nearly depth-uniform (Larson and Sunamura, 1993; Petti and Longo, 2001b).

Maximum uprush velocities observed on gently sloping natural beaches have approached 2 m s\(^{-1}\) (Beach et al., 1992; Butt and Russell, 1999), whereas on steeper beaches, uprush flows are generally stronger and may range up to 3.5 m s\(^{-1}\) (Hughes et al., 1997a; Masselink and Hughes, 1998). The timing of maximum velocities recorded by a current meter can vary depending on the history of the current meter location with respect to the swash zone. If the current meter is ‘dry’ before being inundated by the uprush, the maximum velocity occurs instantaneously (Hughes and Baldock, 2004; Hughes et al., 1997a; Masselink and Hughes, 1998; Puleo et al., 2000; Masselink et al., 2005), but if the current meter is already submerged, the maximum uprush velocity may occur shortly after the leading edge passes (Butt and Russell, 1999; Osborne and Rooker, 1999). A rapid, short-lived acceleration of the flow during the initial stages of uprush has also been observed in laboratory settings using remote sensing techniques (Jensen et al., 2003). Numerical model simulations are equally ambiguous: Hughes and Baldock (2004) used a one-dimensional ballistic model and found no evidence of flow acceleration at the start of the uprush, whereas Puleo et al. (submitted) used a two-dimensional model and did find that the uprush flow briefly accelerates at the start. The presence or absence of flow acceleration is important, because it may affect the sediment transport potential of the uprush (Nielsen, 2002); the issue is perhaps best resolved by acknowledging that it is possible that the uprush accelerates briefly at the bottom of the swash zone, following bore collapse, but that flow acceleration during the uprush does not occur further up the beach (Ballock and Hughes, this issue).

Flow reversal, generally associated with maximum runup levels, corresponds to maximum water depths on dissipative beaches (Zelt, 1991; Masselink et al., 2005), but occurs after the maximum water depth is obtained on steeper beaches (Hughes, 1992; Hughes et al., 1997a). It is important to understand that the initiation of flow reversal and backwash motion is dependent upon the location on the foreshore. For instance, the backwash motion across the lower swash zone may start before the uprush reaches its maximum landward extent (Raubenheimer et al., 1995; Raubenheimer and Guza, 1996; Hughes et al., 1997a; Puleo and Holland, 2001), resulting in a thinning of the swash tongue. This has implications when trying to ascertain the importance of uprush vs backwash flow durations, as well as net sediment transport, since these estimates will depend heavily on foreshore location.

While the uprush motion is dominated by turbulent flows originating in the bore or leading edge, backwash motion is dominated by shear derived at the bed (Petti and Longo, 2001b; Cowen et al., 2003). As a result, longer duration backwashes have an associated boundary layer growth that is more distinct than during uprush (Raubenheimer, 2002; Masselink et al., 2005). Backwash flows accelerate under the forces of gravity, frictional processes and cross-shore pressure gradients, but they do not develop their full downslope gravitational potential (Puleo et al., 2003). Like the beginning of the uprush, the end of the backwash is a fuzzy concept and depends on the definition used and how the motions are recorded.

It is generally found that the duration of the uprush is significantly shorter than that of the backwash, whereas peak uprush velocities are either comparable to (e.g., Puleo et al., 2003) or slightly stronger than (e.g., Hughes and Baldock, 2004) peak backwash velocities. As a result, the velocity skewness in the swash zone is predominantly negative (Masselink and Russell, 2006). This has significant implications for sediment transport processes; these will be discussed later in Section 3.2.

2.5. Shear stresses and friction coefficients

Most sediment transport models rely on the bed shear stress as the mobilizing force (e.g., Nielsen, 1992), but direct measurements of shear stresses are difficult to obtain and therefore rarely available. Conley and Griffin (2004) measured bed shear stresses in the field using a flush-mounted, hot film
anemometer and observed a rapid rise and gradual decline in bed shear stress during uprush, and a more symmetric rise and fall of shear stress during backwash. The peak uprush shear stress was nearly twice that of the peak backwash shear stress with the overall ensemble-averaged shear stress time series being skewed onshore. Shear stress estimates based on the Law of the Wall and velocity data collected in a rough bottom laboratory flume (Cox et al., 2000), and through the use of numerical model simulations on a smooth slope (Puleo et al., 2002) displayed similar time series. Masselink et al., (2005) measured swash flow velocities 0.03 and 0.06 m from the bed on a dissipative beach and derived the bed shear stress from the velocity gradient. They also found that the bed shear stress during the uprush was significantly larger than that during the backwash.

Rather than basing estimates for shear stress \( \tau \) from velocity profile data or a numerical model, the typical approach relies on the quadratic stress law using the free stream velocity \( u \), rather than the friction velocity \( u^* \) as

\[
\tau = \rho u^2 |u^*| = \frac{1}{2} \rho u^2 |u|, \tag{2}
\]

where \( \rho \) is the fluid density and \( f \) is an empirical friction factor. In field studies, knowledge of the boundary layer is often unknown, so a single-point current metre measurement is often used in place of \( u \). The use of Eq. (2) presents another difficulty in terms of the appropriate value for \( f \) and much effort has gone into its estimation (Hughes, 1995; Cox et al., 2000; Puleo and Holland, 2001; Archetti and Brocchini, 2002; Cowen et al., 2003; Conley and Griffin, 2004; Raubenheimer et al., 2004). The general consensus based on these studies is that the uprush friction coefficient is equal to, or greater than the backwash friction coefficient, but differences arise depending on the determination method (Eulerian vs Lagrangian measurements). There is no generally accepted explanation for the larger friction coefficients during uprush, but bore turbulence and in/exfiltration effects may be implicated.

3. Swash zone sediment transport

3.1. Field measurements of swash zone sediment transport

One of the main factors that has hampered progress in increasing our understanding of swash zone morphodynamic processes has been the difficulty in obtaining reliable measurements of the sediment transport signal (Fig. 4). High-resolution (spatial and temporal) measurements of the beachface morphology, obtained either manually (Duncan, 1964; Eliot and Clarke, 1986; Masselink et al., 1997) or by remote sensing techniques (Holland et al., 2001) can be used to derive net sediment transport rates in the swash zone. Sediment traps (James and Brenninkmeyer, 1977; Hardisty et al., 1984; Masselink and Hughes, 1998; Jackson et al., 2004) and pump samplers (Kroon, 1991) measure the bulk sediment load and give information on event-scale sediment transport rates, for example, the transport over an uprush/backwash cycle. On the other hand, instantaneous suspended sediment fluxes can be obtained by the product of flow velocity and sediment concentration (derived from optical devices; Beach et al., 1992; Butt and Russell, 1999; Osborne and Rooker, 1999; Puleo et al., 2000; Masselink et al., 2005).

It is now well established that transport rates in the swash zone are much higher than in the surf zone with suspended sediment concentrations frequently exceeding 100 kg m\(^{-3}\) close to the bed.

![Fig. 4. Collection of sediment transport data in the swash zone: (a) instantaneous suspended sediment flux measurement using co-located current meters and suspended sediment sensors; (b) determination of the total load transport across the swash zone using sediment traps; and (c) using stakes inserted into the beach to monitor bed level changes to derive net sediment transport rates.](image-url)
(Beach and Sternberg, 1991; Butt and Russell, 1999; Osborne and Rooker, 1999; Puleo et al., 2000; Masselink et al., 2005) suggesting large concurrent sediment transport rates. For example, Hughes et al. (1997a) deployed total load sediment traps in the swash zone of a low-energy, steep beach and found that the amount of sediment transported by a single uprush was typically 10 kg m$^{-1}$ beach width. The uprush sediment transport load was two to three orders of magnitude greater than the net transport per swash cycle inferred from surveys of beach profile change; thus, net sediment transport in the swash zone is a small difference between two large quantities (see also Masselink and Hughes, 1998; Osborne and Rooker, 1999).

Recalling that uprush and backwash flows differ in their physical description, it seems logical that the sediment transport processes during these phases of the swash flow would also be different. A general description of the sediment dynamics over a swash cycle is presented in Fig. 5. The extent, duration and timing of the transport modes are speculative and depend very much on the type of swash event, the characteristics of the bed material and the location within the swash zone. Flow velocities, suspended sediment concentrations and suspended fluxes are maximum at the start of the uprush when the flow is most turbulent. The sediment is suspended relatively high into the water column and the dominant mode of transport is expected to be suspended load, with sheet flow also being important. Swash flow energetics decrease rapidly following the arrival of the swash front, resulting in the settling of the suspended sediment to the bed, leaving the water clear around the time of flow reversal. During the backwash, the swash flow progressively accelerates and, accordingly, maximum suspended sediment concentrations and fluxes occur at the end of the backwash. The flow during the backwash is less turbulent than during the uprush, but super-critical flow conditions may prevail at the end of the backwash. The suspended sediment is confined relatively close to the bed and the dominant mode of sediment transport during the backwash is expected to be sheet flow, with suspended load also being important.
The difference between uprush and backwash sediment transport ultimately rests with the difference in their hydrodynamics, discussed in Section 2. The turbulence associated with the collapsing bore, aided perhaps by the short phase of flow acceleration immediately following bore collapse, is likely to be responsible for much of the suspended sediment that is observed in the swash zone at the start of the uprush (Butt and Russell, 1999; Puleo et al., 2000).

As indicated earlier, bore motion can supply high shear stresses, representing an efficient sediment suspending mechanism that has been likened to a bulldozer (Nelson and Miller, 1974). This notion has been corroborated from studies that obtained suspended sediment concentrations on a natural beach and showed that the concentration was highest and nearly depth-uniform at the bore and leading edge of the swash where the turbulence is generated (Osborne and Rooker, 1999; Puleo et al., 2000; Voulgaris and Collins, 2000; Butt et al., 2004).

Based on this past work it appears that much of the sediment that is transported during uprush occurs as suspended load, loosely defined as mobilized sediment that is supported by turbulent fluctuations, rather than grain-to-grain interactions (bedload).

Unlike the uprush, the backwash is generally dominated by bed-generated turbulence, rather than surface-generated turbulence, suggesting that sediment mobilization and transport during backwash typically occurs near the bed. Field studies of sediment transport have shown that the suspended load is more confined to the bed during the backwash (Butt and Russell, 1999; Puleo et al., 2000; Masselink et al., 2005), pointing towards bedload dominance. Bedload-dominated backwash sediment transport was also found by Horn and Mason (1994) using sediment traps (bedload was defined as transport occurring below 1 cm) on four separate beaches. Other work, such as that by Hughes (1992), observed a ‘slurry’ of sand and water during backwash that is more analogous to debris flow, and may more readily be described by sheet flow conditions where the excess shear stress is large (Wilson, 1987). Under such conditions, the flow thickness is on the order of 10–30 times the grain diameter for the swash zone of sandy beaches (Hughes et al., 1997a), and if this is the case, then the measurements of Horn and Mason (1994) may actually have been suspended load, rather than bedload if the transport was occurring under sheet flow conditions. However, only one field investigation has, thus far, claimed to investigate sheet flow sediment transport in the swash zone (Yu et al., 1990).

Difficulties in describing near-bed sediment transport in the swash zone are immediately evident due to subtleties in vernacular (bedload vs near-bed suspended load vs sheet flow) and the actual physics. In reality, sheet flow is a special case of bedload where the excess shear stress is large and bed forms are non-existent. In the swash zone, bed forms are rare except under hydraulic jumps, typically at the seaward edge, suggesting that most near-bed sediment transport in the swash zone occurs as sheet flow. Until more robust sediment transport measurements are made that can accurately distinguish between the various phases some ambiguity will persist.

Sediment transport during the backwash can be dominated by the suspended sediment component at the end of the backwash due to the formation of hydraulic jumps or swash interactions. Butt and Russell (1999) and Osborne and Rooker (1999) measured suspended sediment fluxes in the swash zone of a high-energy dissipative beach and emphasised the occurrence of hydraulic jumps at the end of the backwash, when super-critical flow conditions prevail, resulting in sharp increases in the suspended sediment concentration. According to Osborne and Rooker (1999) these elevated sediment concentrations may lead to advection of suspended sediment into the inner surf zone and may also enhance sediment concentrations during subsequent uprush events.

3.2. Comparison of field data with sediment transport models

There have been only very limited attempts at relating measured sediment transport fluxes in the swash zone to empirical models. Masselink and Hughes (1998) and Masselink and Li (2001) measured the total load transport of individual swash events and correlated the sediment load of each event to the flow velocity for both the wave uprush and backwash. The sediment load displayed a strong relationship with the time-averaged velocity cubed, consistent with equations for both bedload transport and total load transport under sheet flow conditions (e.g., Nielsen, 1992). Validation of the energetics-based model of Bagnold (1966) revealed different constants of proportionality for wave uprush and backwash, with the
uprush value being approximately twice that obtained for the backwash. Validation of a modified Shields parameter (to account for the effect of a sloping bed) also indicated different coefficients, suggesting that neither sediment transport model adequately accounts for the disparate nature of the two phases of the swash cycle. A similar approach, this time involving suspended sediment transport measurements collected from a dissipative swash zone, was followed by Masselink et al. (2005). They also found that the suspended sediment flux measured at the mid-swash position was strongly related to the bed shear stress through the Shields parameter. If the bed shear stress was derived from the vertical velocity gradient (using the Law of the Wall), the proportionality coefficient between shear stress and sediment transport rate was similar for the uprush and the backwash. If the bed shear stress was estimated using the free-stream flow velocity and a constant friction factor (using the quadratic stress law), however, the proportionality factor for the uprush was approximately twice that of the backwash.

According to Puleo et al. (2000), however, energetics-based models are of limited use in the swash zone. They measured suspended swash zone sediment transport on a steep beach under energetic surf zone conditions and demonstrated that in the lower part of the swash zone, bore-generated turbulence may affect sediment suspension in the swash zone during the uprush (see also Butt et al., 2005), whereas flow duration and the development of a boundary layer may play a significant role in controlling sediment suspension during the backwash. The enhanced sediment suspension due to bore turbulence at the start of the uprush may perhaps be accounted for in a swash zone sediment transport model through an additional fluid acceleration (Puleo et al., 2003), kinetic energy (Butt et al., 2004) or turbulence (Hsu and Raubenheimer, this issue) term.

3.3. Swash hydrodynamic factors affecting sediment transport

It was discussed in Section 2 that the uprush phase of the swash flow is characterised by similar velocities, but shorter durations than the backwash, and that, as a result, the velocity skewness in the swash zone is directed offshore (Masselink and Russell, 2006). Numerical models of swash hydrodynamics also predict offshore skewness in the swash zone (e.g., Pritchard and Hogg, 2005). Cross-shore sediment transport in the nearshore zone is generally modelled using energetics-based formulations that consider the sediment transport rate a function of high-order velocity moments ($u'$ for bedload and $u^4$ for suspended load; Bailard, 1981). If such models are applied to the swash zone, the offshore-directed skewness result in a bias towards offshore transport (Elfrink and Baldock, 2002), especially if the fact that sediment is more easily transported downslope is also considered. If this were the case, beaches should always be in an eroding state; therefore, some other mechanism must exist to enhance the uprush transport to counteract this offshore bias. A pragmatic solution to this problem has been to use different proportionality coefficients between sediment transport rate and flow velocity for the uprush and backwash phase of the flow (Masselink and Li, 2001), but such ‘fixes’ are not very helpful in understanding the physics driving the mechanisms enhancing onshore transport.

Energetics-based models rely on the assumption that the sediment transport rate $q$ is related to the instantaneous bed shear stress $\tau$ according to $q \propto \tau^n$, where $n$ is generally larger than 1. In the field, bed shear stress is usually estimated from the free-stream flow velocity through use of some type of quadratic stress law: $\tau \propto f u^2$, where $f$ is a friction coefficient. The swash velocity measured some distance from the bed may, however, not be directly related to the bed shear stress. For example, Cox et al. (2000) and Conley and Griffin (2004) both found that the friction coefficient during the uprush is significantly larger than during the backwash, and therefore for a given swash velocity, the bed shear stress during the uprush will be larger than during the backwash.

Enhanced bed shear stress and sediment transport during uprush have been attributed to infiltration effects (see Horn, this issue for a review of through-bed flows in the swash zone). Most commonly mentioned are infiltration losses during the uprush through percolation into the unsaturated beach, favouring uprush sediment transport and promoting the development of a steep beachface (Grant, 1948; Duncan, 1964; Quick, 1991; Turner, 1995). The effect of such infiltration losses on beach morphology is significant, especially on gravel beaches (Masselink and Li, 2001), but its role is implicit through a reduction in the strength of the backwash: swash flow field measurements include
the effect of swash infiltration losses. It is the effect of in/exfiltration across the saturated beachface that are of relevance here. On the one hand, infiltration can modify the boundary layer by allowing for streamlines to squeeze closer to the bed, resulting in increased shear stresses (Watters and Rao, 1971; Oldenziel and Brink, 1974; Conley and Inman, 1994). On the other hand, infiltration imparts a stabilizing force by inducing a downward pressure on the sediment grains (Martin and Aral, 1971; Watters and Rao, 1971). Conversely, exfiltration reduces boundary shear stresses by dilating the boundary layer, and destabilizes the bed by imparting an upward force on sand grains. With the opposing in/exfiltration effects on hydrodynamic and bed stabilization noted, analysis has been directed at determining when one effect should dominate over the other (Nielsen, 1998; Turner and Masselink, 1998; Butt et al., 2001; Karambas, 2003).

These studies indicate that when the sediment size is below a certain value \(D_{50} = 0.4–0.6 \text{ mm}\), stabilizing and destabilizing forces are more important than boundary layer modification, while above this cut-off, boundary layer modification should dominate. According to Butt et al. (2001) and Karambas (2003), in/exfiltration effects favour onshore transport for coarser grains, and offshore transport for finer grains, but the net effect is relatively modest.

Two additional factors responsible for enhanced bed shear stress during uprush are bore turbulence and flow acceleration. In the case of turbulence, bore collapse or backwash/uprush collision can mobilise and suspend sediment due to violent bore collapse or backwash/uprush collision can mobilise and suspend sediment due to violent mixing (e.g., Puleo et al., 2000; Butt et al., 2004). In addition, the sediment suspended by these processes may then be advected both seaward and landward by subsequent flows. Flow accelerations may occur at the very beginning of uprush when the flow quickly changes from offshore to onshore. The short burst of acceleration may induce a horizontal pressure gradient enhancing sediment transport (Drake and Calantoni, 2001), or cause flow streamlines to squeeze closer to the bed increasing shear stresses over a steady flow of the same magnitude.

The failure of the energetics approach to often predict even the direction of swash zone sediment transport correctly may also be because the sediment load during the uprush is not locally entrained, but is advected into the swash zone by surf zone processes, particularly bore collapse (Hughes et al., 1997b; Elfrink and Baldock, 2002).

In this case, sediment fluxes and morphological change in the swash zone are more related to the amount of sediment entrained by bore collapse and the settling properties of the suspended material, than the instantaneous bed shear stress. The effect of advection of pre-suspended sediment has been directly addressed in field studies by Jackson et al. (2004), and in sediment transport models by Kobayashi and Johnson (2001) and Pritchard and Hogg (2005). Sediment advection from the surf zone is probably especially significant near the early stages of uprush (Jackson et al., 2004), but the rapid decrease in measured sediment concentrations behind the bore seems to suggest otherwise for the remainder of the swash cycle (Puleo et al., 2000; Butt et al., 2004). The importance of sediment advection is expected to be greatest for fine sediment sizes and short uprush durations.

Advection of suspended sediment within the swash zone may also be important through the concepts of ‘settling lag’ and ‘scour lag’. These concepts derive from the estuarine sediment transport literature (Postma, 1961), whereby settling lag refers to the time required for suspended particles to settle to the bottom through slowly flowing water (i.e., advection within the swash zone), and scour lag is a result of the higher flow velocities needed to re-suspend a deposited particle than to keep it in suspension. Maximum suspended sediment concentrations occur at the start of the swash cycle at the bottom of the beach and settling lag enables suspended sediment particles to be transported to the top of the swash zone, despite the fact that uprush velocities may well be below the entrainment threshold. At the time of flow reversal, the water is generally clear, indicating that the suspended sediment has settled to the bed prior to the start of the backwash (Puleo et al., 2000; Masselink et al., 2005). As a result of scour lag, the backwash may not be able to remove many sediment particles from the top of the swash zone, because the flow velocities remain below the entrainment threshold. Settling lag and scour lag are significantly influenced by the fall velocity of the suspended sediment and the duration of the swash flow, but are especially affected by the longshore component of the swash flow. A period of ‘slack water’ around flow reversal is required for settling and scour lag to occur. When the swash flow is characterised by a significant alongshore component, however, sediment particles will remain in suspension during the time of flow reversal and will not settle to the bed at the end of the uprush. It is suggested that the erosion potential
is extra large under such conditions (Masselink and Russell, 2005).

4. Morphology and morphological change in the swash zone

4.1. Beachface gradient

The beachface is the sloping section of the beach profile normally exposed to the action of swash and backed by a sub-horizontal berm, and may be fronted by a beach step (Hughes and Turner, 1999). The shape of the beachface ranges from planar to concave, although under conditions of profile adjustment, usually accretion, the beachface may have a convex shape (Sonu and van Beek, 1971; Sonu and James, 1973; Makaske and Augustinus, 1998). When beach cusp morphology is present, the beachface is steep and convex at cusp horns, and less steep and concave at cusp bays (e.g., Masselink et al., 1997).

The most characteristic feature of the beachface is its steep gradient compared to the rest of the beach profile and this is ascribed to swash motion tending to favour onshore, rather than offshore sediment transport (see Section 3.3). The beachface is in dynamic equilibrium with swash motion when the amount of sediment transported onshore by the uprush is equal to that transported seaward by the backwash, and the associated equilibrium gradient represents the balance between onshore swash asymmetry and the downslope component of gravity (Hardisty, 1986). It should be noted that the ‘equilibrium beachface gradient’ is not necessarily the same as the ‘equilibrium swash zone gradient’, because particularly on tidal beaches, the beachface is not solely shaped by swash processes, but is also affected by surf zone and shoaling waves (Wright et al., 1982). Care should also be taken in interpreting previous field investigations due to inconsistencies in the definition of the beachface gradient. For example, Bascom (1951) uses the gradient around the mid-tide level (i.e., gradient of the intertidal zone), whereas Dubois (1972) computes the gradient from the upper limit of the uprush to the lower limit of the backwash (i.e., gradient of the swash zone).

The equilibrium beachface gradient decreases with wave height, and increases with wave period and sediment size (Bascom, 1951; Kemp and Plinston, 1968; Dalrymple and Thompson, 1976; Sunamura, 1984). By far the most important factor controlling the gradient of the beachface is the sediment size and Bagnold (1940) contends that it is in fact the only factor of significance. There are (at least) two explanations for the dependence of beachface gradient on sediment size found in nature (Komar, 1998). On beaches consisting of relatively coarse sediments \( (D_{50} > 1 \text{ mm}) \), the sediment size controls the equilibrium beachface gradient through its effect on swash infiltration (Grant, 1948; Quick, 1991). Percolation of uprush water into the unsaturated beachface weakens the backwash with respect to the uprush. The ensuing swash asymmetry enhances onshore sediment transport, resulting in a steepening of the beachface until a gradient is attained whereby the onshore force due to swash asymmetry is balanced by the offshore gravity component. On beaches consisting of relatively fine sediments \( (D_{50} < 1 \text{ mm}) \), suspended sediment transport controls the beachface gradient. In this case, the beachface gradient is expected to increase with the ability of the sediments to resist transport (Dean, 1973) and will increase with the sediment fall velocity (a function of the size and density of sediment particles). Correlation between beachface gradient and sediment properties cannot be used to identify the most important process controlling the gradient, because sediment size, permeability and fall velocity are highly inter-related. When beachface gradient data are plotted vs each of the three sediment characteristic parameters, similar trends are observed, providing no discrimination against either the mechanism based on the sediment permeability or the sediment fall velocity (Masselink and Li, 2001).

4.2. Beachface morphological change

The response of the beachface to changing hydrodynamic conditions is traditionally perceived in terms of changes in equilibrium conditions on the beachface (too gentle or too steep), resulting in net onshore or offshore sediment transport. Of particular significance is the recognition of seasonal and cyclic changes in berm/bar morphology and onshore/offshore transport in response to storm-induced changes in the wave steepness (Komar, 1998). If the beachface is flatter than the equilibrium gradient, the uprush moves more sediment than the backwash, inducing net onshore sediment transport. Sediment is eroded from the lower part of the beach and is deposited on the upper part, resulting in a steeper beachface (Fig. 6a). If the beachface is too
steep compared to the equilibrium gradient, the backwash moves more sediment than the uprush, inducing net offshore sediment transport. Sediment is eroded from the upper part of the beach and is deposited on the lower part, resulting in a flatter beachface (Fig. 6b). In both cases, morphological change (beachface steepening and flattening) will continue until a new equilibrium is attained. The beachface morphological changes shown in Fig. 6a and b are somewhat unrealistic, however, in that they require maximum accretion and erosion to occur across the least energetic part of the beachface in the upper swash region. Maximum bed level changes are more likely to occur around the mid-to-lower swash position and the development of a convex profile during beachface accretion, and a concave profile during beach erosion, such as displayed in Fig. 6c and d, respectively, are more likely to occur.

The equilibrium beachface concept and its role in governing net cross-shore sediment transport in the swash zone is appealing, and the association between offshore (onshore) sediment transport and beach profile flattening (steepening) has become one of the main tenets in nearshore research. It is often ignored, however, that beachface erosion during storm conditions is rarely accomplished by swash processes, but generally occurs as a result of surf zone processes. During storms, the water level in the surf zone is elevated due to wave set-up. As a result, the upper part of the beach (i.e., the beachface) becomes too steep in relation to this new water level and surf zone processes (breaking waves and bed return flow) start eroding the beachface. This results in a flattening of the beachface, not because the backwash is stronger than the uprush, but because surf zone waves are operating on a part of the beach shaped by swash processes. In fact, during major storms, swash processes are more likely to operate on the backshore region of the beach, or even affecting the fore dunes, than the beachface.

Beachface morphological change is commonly investigated over event-type time scales, for example, over a tidal cycle or during a storm. Instantaneous observations of beachface adjustment over a time scale of minutes are less common, but have been made using stakes or rods installed into the beach and measuring these at regular intervals (Fig. 4c). Most of these investigations focused on identifying cyclic patterns of beachface erosion and accretion in response to tidal water level variations, specifically erosion of the lower (saturated) part and accretion on the upper (unsaturated) part of the beachface (Duncan, 1964; Clarke et al., 1984; Eliot and Clarke, 1988; Nordstrom and Jackson, 1990). The method has
also been applied to investigate beachface response to changing wave conditions, and has proven to be particularly useful for measuring beach cusp morphological change (Eliot and Clarke, 1986; Masselink et al., 1997).

4.3. Morphodynamic feedback

Feedback between morphology and hydrodynamics is an essential component of the swash zone/beachface morphodynamic system (Fig. 1) and can be considered at two main spatial scales: (1) interactions between the morphodynamic systems of the beachface and the surf zone (‘global’ feedback); and (2) interactions within the beachface morphodynamic system (‘local’ feedback). Morphodynamic feedback between the beachface and surf zone is relatively straightforward and will only be addressed briefly here. Beachface erosion by offshore sediment transport generally results in sediment deposition in the surf zone, possibly in the form of nearshore bar morphology (e.g., Wijnberg and Kroon, 2002). There will be a shift in the location of wave energy dissipation from the lower beachface to the surf zone, resulting in reduced amounts of wave energy reaching the base of the beachface and less energetic swash dynamics. Onshore sediment transport from the surf zone to the beachface, on the other hand, may cause an increase in the water depth at the base of the beachface. Wave energy dissipation will shift from the surf zone to the beachface, exposing the beachface to higher waves and more energetic swash dynamics. A change in the beachface gradient also modifies the reflectivity of the beach and may increase (in case of steeper beachface) or decrease (in case of flatter beachface) the amount of reflected wave energy in the surf zone.

Morphodynamic feedback within the swash zone is provided by the beachface gradient, because it constitutes the main factor to balance the onshore swash asymmetry. Compared to sediment transport across a horizontal gradient, a correction factor $C_\beta$ can be formulated to account for the effect of a sloping bed (Fredsoe and Deigaard, 1992)

$$C_\beta = \cos \beta \left( 1 - \frac{\tan \beta}{\tan \phi} \right) \quad (3a)$$

for upslope flow and

$$C_\beta = \cos \beta \left( 1 + \frac{\tan \beta}{\tan \phi} \right) \quad (3b)$$

for downslope flow, where $\beta$ is the beach angle and $\phi$ is the friction angle of the sediment ($\tan \phi = 0.63$). The slope correction factor for a moderately steep beach ($\tan \beta = 0.1$) is 0.84 and 1.15 for upslope and downslope sediment transport, respectively. The steeper the beach, the more upslope transport is inhibited and the more downslope transport is enhanced. On a steepening and accreting beachface it therefore becomes increasingly difficult to move sediment upslope and at some stage an equilibrium will be reached. Similarly, on a flattening and eroding beachface the slope contribution to offshore transport progressively decreases and equilibrium will also be attained. Hardisty et al. (1984) formulated a simple morphodynamic model for beachface response based on the beachface gradient and the onshore swash asymmetry and this model was subsequently used by Masselink and Li (2001) to investigate the effect of swash infiltration on the beachface gradient.

Eq. (3) accounts for the direct effect of the beachface gradient on sediment transport in the swash zone, but there are also indirect (and equally significant) effects that have hardly been addressed in the literature. For example, the beach gradient at the bottom of the swash zone controls the type of breaker or bore and thus plays an important role in determining the amount of turbulence and suspended sediment advected into the swash zone at the start of the uprush. For spilling and surging breakers, the onshore swash asymmetry derived from the wave breaking process will be limited, but plunging and collapsing breakers are expected to greatly favour uprush sediment transport, hence promoting the development of a steep gradient. There is clear scope for positive morphodynamic feedback between a steepening beachface, and the increased turbulence and enhanced sediment transport during the uprush, allowing rapid morphological change to take place.

The beach gradient also affects the sediment transport through its effect on the swash hydrodynamics. Specifically, the period of the swash motion is controlled by the bed gradient, and a steepening (flattening) of the beachface will result in a decrease (increase) of the swash period. The importance of this has been addressed by Holland and Puleo (2001) who hypothesised that beachface morphological response represents an attempt to minimise the difference between swash duration $D$ and incident-wave period $T$ (see also Kemp, 1975).
For $D/T<1$, swashes are uninterrupted (‘free’) and this is thought to promote offshore sediment transport in the swash zone and flattening of the beachface. For $D/T>1$, however, swash motion is characterised by interactions and these are assumed to promote onshore sediment transport in the swash zone and steepening of the beachface. Beach flattening and steepening results in an increase and a decrease in the swash period, respectively, and equilibrium conditions on the beachface are expected for $D/T = 1$. The model proposed by Holland and Puleo (2001) has merit in that swash interactions serve as the driving force behind beachface profile adjustment and can be used to formulate a morphodynamic model (i.e., a model that accounts for feedback).

A different morphodynamic equilibrium model can be defined based on the assumption that sediment suspension is the main mode of sediment transport in the swash zone. Several processes have been identified in Section 3.3 that promote uprush sediment transport, including bore turbulence, flow acceleration, sediment advection and settling/scour lag. For the uprush to optimally benefit from this advantage, the sediment transported during the uprush must settle to the bed before flow reversal, because part of the uprush advantage will pass on to the backwash if there is still sediment in suspension. Whether or not the sediment suspended during the uprush settles to the bed before the start of the backwash can be parameterised by

$$
\Omega = \frac{z_s}{w_s T_u},
$$

where $w_s$ is the fall velocity of the suspended sediment, $T_u$ is the uprush duration and $z_s$ is the height to which the sediment is suspended (note that the present approach is identical to that followed by Gourlay (1968) and Dean (1973) in their derivation of the dimensionless fall velocity). In reality, there is no single height above the bed at which all sediment particles are suspended, so $z_s$ is best seen as the centre of mass of the suspension cloud. As long as $\Omega < 1$, most sediment suspended during the uprush will settle to the bed prior to flow reversal and the beachface may experience net onshore sediment transport and steepening. For $\Omega > 1$, however, significant amounts of uprush-entrained sediment will be taken up by the backwash and may result in net offshore sediment transport and beachface flattening. Similar to the swash interaction model of Holland and Puleo (2001), the morphodynamic feedback in the sediment suspension model is provided through the control of the beachface gradient on the uprush period. On a steepening beachface (due to onshore sediment transport), the uprush duration progressively decreases, and $\Omega$ increases. Similarly, on a flattening beachface (due to offshore sediment transport), the uprush duration progressively increases, and $\Omega$ decreases. An equilibrium condition may be defined in terms of the $\Omega$ value (not necessarily $\Omega = 1$), but it should be borne in mind that this morphodynamic model is very tentative and does not consider bed load transport, nor sediment advection from the surf zone.

5. Conclusions and future perspectives

Up until the mid-1990s, studies of sediment transport processes in the swash zone were few and far between, and subsequently our understanding and modelling capabilities of this important part of the nearshore was limited. The last decade has seen, however, an increased interest in the swash zone and significant advances have been made due to laboratory and field studies.

It is now very evident that there are some fundamental differences between the uprush and backwash phases of the swash flow. The uprush is generally dominated by bore turbulence, especially on steep beaches and in the lower swash zone, whereas backwash flows are dominated by turbulent dissipation resulting from boundary layer formation near the bed. As a result, sediment tends to be mixed high into the water column and transported as suspended load during uprush, whereas sheet flow and bedload dominate during backwash. Interactions occur between the swash motion and the beach groundwater table in the form of infiltration (mainly, but not solely during uprush) and exfiltration (mainly, but not solely during backwash); these have a modifying effect on the sediment transport process. Flow accelerations tend to be less than gravitational acceleration throughout much of the swash duration, but a short burst of accelerating uprush may occur during the bore collapse process. For the most part, shear stresses tend to be larger during uprush than during backwash, but of a shorter duration. Friction coefficients are equal to or larger during uprush than backwash and are likely to vary over the swash cycle. Flow velocities are similar between uprush and backwash, but flow...
durations are typically unequal with a slightly longer backwash. As a result, the velocity skewness is directed offshore.

The hydrodynamic differences between uprush and backwash have far-reaching implications for sediment transport processes. If sediment fluxes in the swash zone are modelled using free-stream flow velocities and energetics-based transport models (as is commonplace in the surf zone), beaches cannot exist due to the prevalence of (offshore) backwash flows. There are, however, a number of (related) processes that promote uprush sediment transport and thereby compensate for the offshore-directed velocity skewness, including in/exfiltration effects, flow acceleration, bore turbulence, settling lag, scour lag and sediment advection from the surf zone. The relative importance of each of these processes has not been established yet, but is likely to depend on the type of swash zone. For example, the roles of bore turbulence and advection are expected to be particularly significant on steep beaches dominated by incident swash, whereas settling lag may be especially important on beaches comprising of fine sediments.

Compared to the advances made in swash hydrodynamics, relatively limited progress has been made during the last decade with regards to our understanding of beachface morphological change and equilibrium (except with respect to the formation of beach cusp morphology). The difficulty is that net sediment transport in the swash zone is the difference between two very large numbers, neither of which can be quantified very well. We therefore lack the ability to predict beachface morphological change and have only a heuristic understanding of whether swash zone erosion or accretion will occur. It is clear, however, that the beachface cannot be considered in isolation from the surf zone and that the two zones are strongly linked through feedback processes. The swash zone itself is also a morphodynamic system and any morphological development will have direct and indirect effects on swash hydrodynamics and sediment transport processes. These indirect effects have only just begun to be included in morphodynamic models of the swash zone.

We would like to have concluded this review by providing a short list of key issues that require addressing to help guide further research (see Puleo and Butt (this issue) for some key issues). However, it is fair to say that practically all aspects of swash zone morphodynamics discussed here need attention, especially in a field context. For example, only very few measurements of turbulence and virtually no data on sheet flow and bedload sediment transport are available from the swash zone. Similarly, the relative importance of landward-directed flow accelerations to uprush sediment transport, and the net effect of swash in/exfiltration remain to be established. We feel, however, that most progress can be made by addressing the role of sediment advection, both from the surf zone into the swash zone and within the swash zone (where it results in settling lag). Sediment advection is believed to play a key role in controlling the sediment transport asymmetry in the swash zone, and therefore the morphological development, but has received hardly any attention in field experiments (nor laboratory experiments). A second issue that we feel is potentially very important, but has neither received much research focus is the role of longshore swash motion. Based on our field observations on sandy beaches, it appears that beachface erosion by swash processes is rather uncommon and seems to be restricted to instances where swash action has a significant alongshore component, either due to obliquely incident waves and strong alongshore swash motion, or three-dimensional (beach cusp) morphology. We hypothesise that under such conditions, when there is no slack-water phase during flow reversal, the sediment remains in suspension throughout the swash cycle, thereby promoting offshore sediment transport.

References


Baldock, T.E., Hughes, M.G. Field observations of instantaneous water slopes in the inner surf and swash zones.
Continental Shelf Research, this issue, doi:10.1016/j.csr.2006.02.003.


Bradshaw, M., Bores and swash on natural beaches, 82/4, 1982, Sydney University (Australia), Coastal Studies Unit.


Horn, D.P., Measurement and modelling of groundwater flows in the swash zone. Continental Shelf Research, this issue.
Hsu, T. J., Raubenheimer, B., Modelling sediment transport in the inner-surf and swash zones. Continental Shelf Research, this issue.


