Hydrodynamics and Cross-Shore Sediment Transport in the Swash-Zone of Natural Beaches: A Review

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ABSTRACT

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The high velocities and suspended sediment concentrations in the swash-zone mean that the sediment transport processes in this zone are likely to be important contributors to shoreline erosion and accretion. However, studies of hydrodynamics and sediment transport in the swash-zone have been relatively few compared with those in the rest of the nearshore zone. Studies of swash-zone hydrodynamics have included run-up measurements using electrical resistance and capacitance devices, as well as cameras. Run-up has been modelled mostly using the non-linear shallow water equations. Sediment transport studies in the swash-zone require instrumentation which can unobtrusively obtain measurements close to the bed, therefore, very few data exist so far. Studies have been performed in incident-wave dominated relatively low energy conditions on steep reflective beaches, measuring individual swash events, and the sediment transport processes modelled with reasonable success on the uprush only. Studies made on high energy dissipative beaches have found the swash to be dominated by oscillations at infragravity frequencies, with suspended sediment concentrations being 3 to 9 times higher in the swash-zone than the inner surf-zone. The added complication of groundwater influx and outflux is also recognised as an essential area of study, whose processes should be included in any model of the swash-zone sediment transport.

ADDITIONAL INDEX WORDS: *Backwash, bedload, exfiltration, incident wave, infiltration, long-wave, run-up, sheet-flow, suspended load, uprush.*

INTRODUCTION

The morphological behaviour of the coastline is important for a great number of reasons. Erosion and accretion of the shoreline in response to dynamic wave conditions are functions of the overall sediment budget. To predict changes in shoreline morphology, one of the most important parameters which must be predicted is the cross-shore movement of sediment. In most cases, cross-shore sediment transport data is required to validate models of shoreline evolution, and it has been established for some time (*e.g.* SUNAMARA, 1984), that the inclusion of the swash-zone in these studies, is important. However, despite the importance of the swash-zone, this area has been somewhat neglected, especially with regard to sediment transport studies. This neglect is somewhat due to the overall perception that field measurements in the swash-zone are prohibitively difficult to obtain, especially during times of significant morphological change (HUGHES *et al.*, 1997).

The processes acting in the swash-zone are different from and more complex than those acting in deeper water. Complications arise from factors such as the following:

(a) The water in the uprush and backwash phases does not behave in the same way. During the uprush the flow is decelerating, whilst in the backwash it is accelerating.

The duration of backwash is typically longer than the uprush (HUGHES *et al.*, 1997).

(b) Near-bed suspended sediment concentrations in the swash-zone are much higher than those found in the inner surf-zone. BEACH and STERNBERG (1991) found them to be 3 to 9 times greater.

(c) Mechanisms associated with filtration of water into and out of the beach face may modify the sediment transport. This may be due to the combined effects of boundary layer thinning/thickening, and surficial sediment stabilisation/destabilisation leading to possible fluidisation (BAIRD *et al.*, 1996; TURNER and NIELSEN, 1997; NIELSEN, 1998; TURNER and MASSELINK, 1998).

The processes operating in the swash-zone are far from understood. There has been considerable pessimism in the literature, *e.g.* " . . . Too little is known at present to even attempt a description of the basic sediment transport mechanisms in this area" (NIELSEN, 1992); and " . . . The physical description of fundamental sediment transport mechanisms operating within the swash-zone is presently beyond the state of the art." (TURNER, 1995).

Models of shoreline evolution have so far made slow progress in dealing with the swash-zone. Out of the six short-term coastal profile models evaluated by BRØKER-HEDE-GAARD *et al.* (1992), none of them was capable of describing swash-zone processes.

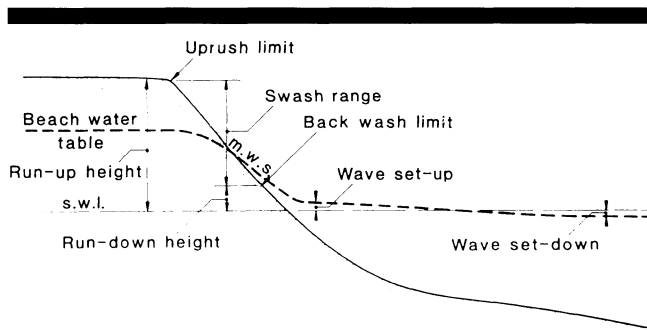This review is confined to describing field studies of swash-

Figure 1. Definitions of set-up, run-up, run-down and watertable. s.w.l = mean water surface; s.w.l. = still water level. (after GOURLAY, 1992)

zone hydrodynamics, sediment transport, and associated modelling, rather than laboratory studies. Observations and attempts at modelling swash-zone hydrodynamics are described, together with swash-zone sediment transport measurements which have only recently being attempted. A description is also given of studies relating to fluctuations in the watertable associated with swash movements, and swash-driven fluxes of water in and out of the beach face.

SWASH-ZONE HYDRODYNAMICS

Definitions of Terms Used in Swash-Zone Hydrodynamics

Field and theoretical work on the concepts of set-up and run-up was done by NIELSEN (1988, 1989), NIELSEN and HANSLOW (1991), and HANSLOW and NIELSEN (1993). Figure 1 shows the relative positions of set-up, run-up, run-down and watertable.

(a) Wave set-up may be defined as a wave-induced increase in mean water surface (m.w.s), where the mean water surface outside the surf-zone is normally identified with the still water level (s.w.l.).

(b) Wave run-up height is defined as the maximum height above s.w.l. reached by the wave uprush.

(c) Wave run-down is defined as the lowest vertical height reached by the backwash of a wave before the next wave starts to run up the beach. The run-down level is normally above s.w.l. when there is considerable dissipation, but may be below s.w.l. on steep reflective beaches.

(d) The swash-range is the vertical distance between run-up and run-down heights. It is normally larger than the wave set-up on dissipative beaches, but smaller than wave set-up on reflective beaches (GOURLAY, 1992).

(e) The watertable may be defined as the mean water surface within the beach material where the mean pore water pressure is zero. The height and shape of the watertable depend partly on the passive characteristics of the sediment which determine its porosity, and partly on the active hydraulic conditions such as wave height, rainfall, and tidal range (NIELSEN, 1988).

The Importance of Long Waves

The existence of long-period ocean waves has been acknowledged for some time, and their importance for sediment transport in the surf-zone has been recognised (e.g. RUSSELL, 1993). It is also logical to assume that they must play an important role in transporting sediment in the swash-zone, since they generally grow in amplitude towards the shoreline. GUZA and THORNTON (1985) observed an increase in infragravity cross-shore velocity variance of between 10 and 100 times, between 5m depth and the shoreline, and MASSELINK (1995) found a four to five-fold increase in infragravity surface elevation variance from a depth of 4m down to 1m.

MUNK (1949) was one of the first to observe long period (30–300 s) sea surface fluctuations in the nearshore. The amplitude of these oscillations was shown to have a quasi-linear relationship with the amplitude of the incident waves seaward of the surf-zone (TUCKER, 1950), and the groups of incident waves were shown to correspond with troughs in the low frequency oscillations.

An explanation of the formation of long-waves was proposed by LONGUET-HIGGINS and STEWART (1964), in terms of radiation stress. Since large waves have a greater mass transport than small waves, then the difference in momentum flux causes water to be expelled from regions of larger waves to regions of smaller waves; this in turn causes a 'set-down wave' which is 180° out of phase with the envelope of the wave-group, but has the same wavelength and period. The model of LONGUET-HIGGINS and STEWART (1964), showed that a group-forced long-wave could be described by:

$$\eta(t) = -\frac{1}{\rho}\left[\frac{S_{xx}(t)}{gh - C_g^2}\right] \tag{1}$$

where $\eta(t)$ is the time-varying sea surface elevation averaged over the incident wave period, ρ is the water density, $S_{xx}(t)$ is the time varying cross-shore radiation stress, h is the incident-period averaged water depth, and C_g is the group speed. The theory predicts a bound long wave travelling at C_g. The hypothesis states that the bound long-wave is then released at the breakpoint of the incident waves, and travels shorewards as a free wave.

An alternative explanation for the formation of low frequency oscillations in the surf-zone was proposed by SYMONDS et al. (1982). Here the long-wave motion is driven by the cross-shore variation in the position of the breakpoint due to the variation in height of the incident waves. A time-varying wave set-up is created, which generates long waves propagating in the shoreward and seaward directions.

After propagation to the shoreline, the long wave is reflected and may either remain trapped to the shore as an edge wave (e.g. HUNTLEY, 1976), or leak out into deeper water. A standing wave may be produced from the interaction between the shoreward-propagating wave and its reflection from the beach-face. The standing waves have a particular cross-shore structure, depending on the mode (HOLMAN, 1981).

Infragravity frequency oscillations have been established as one of the most important mechanisms contributing to the transport of sediment in the surf-zone, and infragravity frequency variations of sediment flux have been found to in-

crease shoreward (*e.g.* BEACH and STERNBERG, 1988; RUS-SELL, 1993). Hydrodynamic studies have indicated that, on flat beaches where breaking dissipates incident wave energy, the infragravity energy is carried through to the shoreline (e.g. GUZA and THORNTON, 1982). Therefore, infragravity fluctuations not only generally increase shoreward but, in incident-saturated conditions, the shoreline becomes increasingly long-wave dominated with increasing offshore wave height. Sediment transport in the swash-zone in high-energy dissipative conditions has actually been found to be highly infragravity-dominated (BEACH and STERNBERG, 1991), although very few studies of this type have been made.

Field Studies of Swash-Zone Hydrodynamics

Field studies of the hydrodynamic processes in the swash-zone have normally been performed using offshore wave-gauges in association with various different types of device to measure either the run-up height (*i.e.* how deep the water is at any given time in a fixed position in the swash-zone), or the run-up distance (*i.e.* the instantaneous cross-shore displacement of the shoreline). It has been pointed out that the difference in reference frame (Eularian or Lagrangian) between these methods may have an important effect on the results (LONGUET-HIGGINS, 1986; BALDOCK *et al.*, 1997).

A study of swash hydrodynamics was performed by GUZA and THORNTON (1981, 1982), as part of the National Sediment Transport Study (NSTS), using run-up wires and pressure sensors on a gently sloping beach. When a large number of run-up heights was compared with the corresponding incident wave heights, and the run-up variance was split into high and low frequency bands, it was found that the incident band energy levels appeared to be independent of incident wave height, (suggesting saturation), but infragravity band swash oscillations were shown to increase approximately linearly with incident wave height (see Figure 2).

A method using time lapse photography with a super-8 movie camera, to measure shoreline position, has been reported by HOLMAN and GUZA (1984). Using this technique, HOLMAN and SALLENGER (1985) obtained a large data set of shoreline positions on a steep beach, with incident wave heights varying between 0.4m and 4m. However, they experienced difficulty determining the backwash position due to the effects of infiltration. The connection between swash oscillations and offshore wave heights was investigated by using a surf-similarity parameter. In this way, the dependency of this relationship upon the degree of surf-zone saturation could be quantified. The dimensionless surf-similarity parameter, the Iribarren number, ξ_0 (BATTJES, 1974) is defined as follows:

$$\xi_0 = \beta \left[\frac{H_0}{L_0} \right]^{-1/2} \tag{2}$$

where β is beach slope, and H_0 and L_0 are the deep-water significant wave height and period respectively. It was found that, for small values of ξ_0 the results were consistent with those of GUZA and THORNTON (1982), but for larger values of ξ_0 (*i.e.* no saturation), the incident frequency swash oscillations were actually related to offshore wave heights.
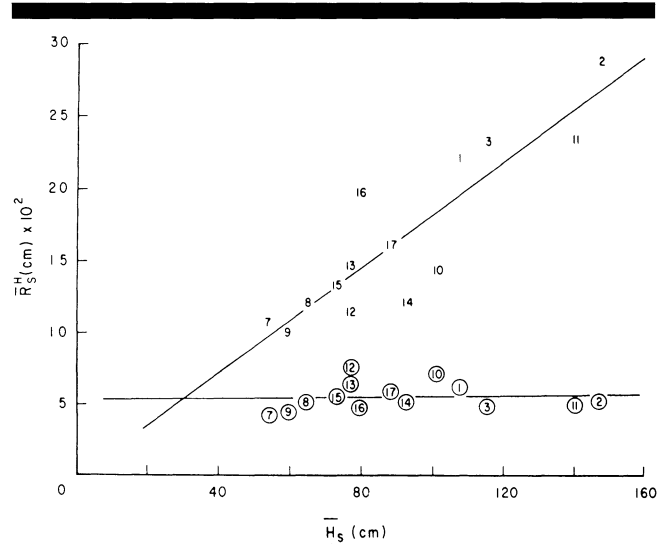

Figure 2. Run-up height obtained from low (<0.05 Hz) and high (>0.05 Hz) frequency swash variances, v. incident wave height. Each number corresponds to a different run, with different offshore wave conditions. Circled numbers represent the high frequencies. (after GUZA and THORNTON. 1982)

The data of Guza and Thornton were reanalysed by HOLMAN (1986) to derive statistical relationships for extreme values of run-up, which were then normalised by H_0 and plotted against ξ_0. For example, regression analysis yielded $R_{max} = 0.55H_0\xi_0$ and $R_{2\%} = 0.45H_0\xi_0$, where R_{max} is the maximum run-up elevation and $R_{2\%}$ is the 2% exceedence elevation. The plots could then be used in conjunction with a storm value of ξ_0 and a design wave height, to estimate a design run-up height. The run-up was also found to be incident dominated with $\xi_0 > 1.5$ or infragravity dominated with $\xi_0 > 1.5$.

Sensitivity of run-up measurements to run-up wire elevation was also investigated by HOLLAND *et al.* (1995). Run-up wires at five elevations were used in conjunction with a modified video technique based on the method outlined by AAGAARD and HOLM (1989), whereby the most landward identifiable edge of the swash tongue was digitised to provide a time-series of shoreline location. It was apparent that the video observations were most consistent with those of the lowest wires, and therefore corresponded with a very near-bed measurement. The significant horizontal run-up excursion and the mean superelevation (set-up) were found to increase with decreasing height above the bed, with maximum values being produced by the video, and the greatest variation within 10cm of the bed. At low infragravity frequencies cross-shore standing wave patterns were observed, but there appeared to be some overamplification of the swash magnitudes relative to a linear standing wave model. The maximum overamplifications occurred at the lowest elevations and at the lowest resolvable frequency (0.005Hz).

A video camera was used by RUESSINK *et al.* (1998) to measure the time-varying shoreline location, during highly dissipative conditions. They confirmed that a relation exists between ξ_0 and R_{ig}/H_0 (where R_{ig} is infragravity swash height).
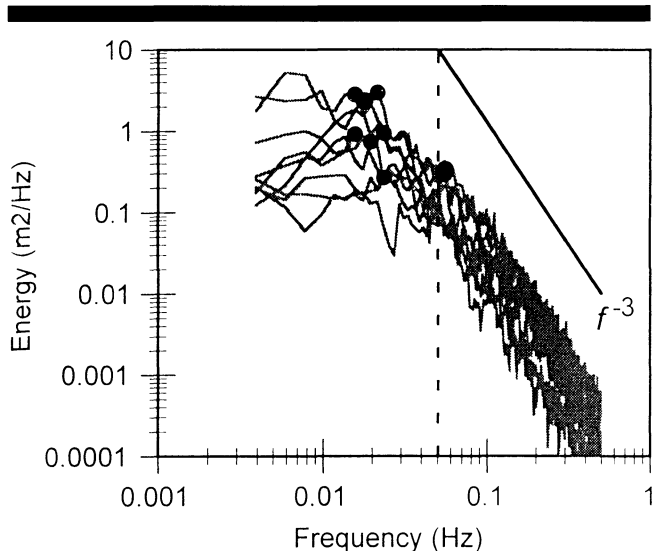
Figure 3. Energy spectra of run-up height, showing how saturation occurs at higher frequencies. The vertical dashed line is the division between the infragravity and incident bands (after RUESSINK et al, 1998).

Figure 4. Overview of published ξ_0 dependencies of R_{ig}/H_0 (after RUESSINK et al, 1998). Line (a) is RUESSINK et al, (1998); line (b) is HOLMAN and SALLENGER (1985); line (c) is HOLLAND (1995), and line (d) is RAUBENHEIMER and GUZA (1996). The single cross is from HOLMAN and BOWEN (1984).

Also investigated was the saturation roll-off in the swash energy spectrum, first suggested by HUNTLEY et al (1977), whereby, for a particular beach slope, R^2 was proposed to depend upon f^4, where R is run-up height and f is frequency. They found the saturated tails in their spectra to decay approximately as f^3 (see Figure 3).

The results of the above studies suggest that, if the beach is sufficiently dissipative to allow the incident waves to become saturated, then the incident frequency fluctuations at the shoreline will not increase with increasing offshore wave height. However, infragravity waves do not break due to their long wavelength and low steepness, and their amplitude at the shoreline will continue to be related to increases in the offshore incident wave height. This concept was recognised by HUNTLEY et al. (1977), whereby it was suggested that swash motions consist of a saturated incident-frequency component and a non-saturated long-wave component.

Figure 4 summarises from the literature how the relation between infragravity swash motions and offshore wave height changes according to the Iribarren number (indicating the degree of saturation). Instrumental differences and different methods of calculation may partly explain the variation between different workers (see RUESSINK et al., 1998).

However, many studies have also taken place in conditions which are not dissipative enough to allow all the incident waves to become saturated (e.g. WADDELL, 1973; SONU et al., 1976; BRADSHAW, 1980, 1982; MIZUGUCHI, 1984). In these types of conditions the incident waves break close to the shore and are transmitted directly to swash motions. Therefore, the existence of two different types of kinematic behaviour of the shoreline has been acknowledged, which has led to difficulty in identifying the approach required for modelling. Furthermore, the existence of long waves at the shoreline directly derived from locally forced grouping has also been recognised,
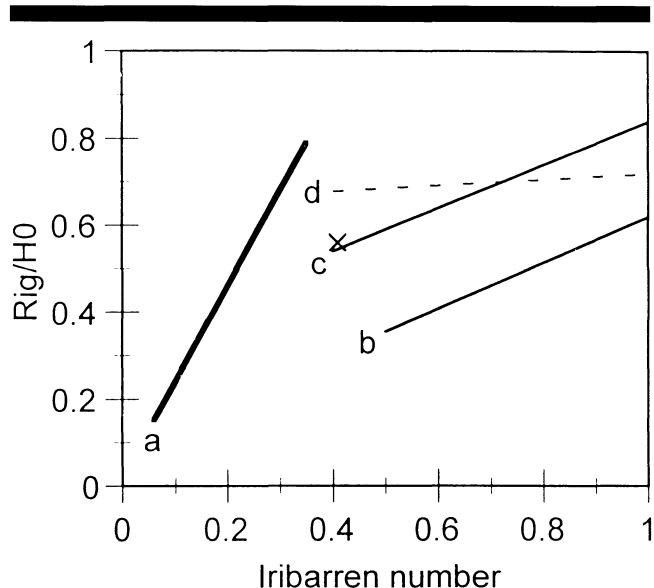
although mainly from the results of laboratory studies (MASE, 1988; BALDOCK et al., 1997).

Modelling Swash-Zone Hydrodynamics

This section describes some of the attempts which have been made to develop models of run-up elevations and spectra. The theoretical description of run-up has been divided between (a): the standing wave hypothesis first proposed by MICHE (1951), whereby the swash motion is dependent upon the amplitude of a cross-shore standing wave produced by reflection of unbroken incident wave energy, (energy from incident waves big enough to break would be dissipated); and (b): the non-linear shallow water theory following bore collapse proposed by HO et al. (1962), and SHEN and MEYER (1963). The latter theory was examined using numerical techniques by FREEMAN and LeMEHAUTE (1964), and AMEIN (1966). The depth-integrated non-linear shallow water equations for motion and continuity are:

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + g\frac{\partial \eta}{\partial x} = 0 \qquad (3)$$

and

$$\frac{\partial[u(\eta + h)]}{\partial x} + \frac{\partial \eta}{\partial t} = 0 \qquad (4)$$

where u is the cross-shore velocity, η is the surface elevation, x is cross-shore distance, g is gravitational acceleration and t is time. These equations were solved numerically by HIBBERD and PEREGRINE (1979) to describe the uprush and backwash of a bore climbing a beach. Many models have subsequently been developed based on this work (e.g. KOBAYASHI

et al., 1987, 1989, 1990; KOBAYASHI and KARJADI, 1994, 1996), with good success at describing the shoreline motion, but still not suitable for further application to sediment transport modelling (HORN, 1997).

A comprehensive study, including field measurements using a cross-shore transect of capacitance probes on a steep beach, was made by HUGHES (1992), to examine the applicability of a model based on the shallow water theory to swash hydrodynamics on a natural beach. It was concluded that the model consistently over-predicted the maximum swash height, shoreline displacement and swash depth, which was thought to be due to the combined effects of friction and infiltration which were not originally considered in the model. It was also shown that the backwash was less well predicted than the uprush, and the behaviour of the backwash 'bore' needed to be studied further, together with the behaviour of granular fluids in the backwash. The non-linear shallow water equations have been used to model the swash height and shoreline position on the uprush only, with the addition of a friction factor (HUGHES, 1995; TURNER, 1995).

RAUBENHEIMER *et al.* (1995) measured the run-up characteristics on a fine-grained, gently sloping beach, using pressure sensors and a series of five run-up wires, stacked vertically. Results showed that (a): wave reflection at the shoreline was greater in the infragravity band than the incident band; and (b): reflection at incident wave frequencies increased with beach slope. There was found to be a predominance of standing wave energy in the infragravity band, and of progressive energy in the incident band. The non-linear shallow water equations were used to model run-up and surf-zone pressure and velocity fluctuations. The model was shown to predict well the shoreward increase of infragravity energy and decrease of incident wave energy. The observed transformation of wave shape (*i.e.* skewness and asymmetry) was also well predicted.

The above study was extended by RAUBENHEIMER and GUZA (1996), who compared results from a model and observations of run-up using vertically stacked run-up wires, from both a gently sloping beach and a steep concave beach, with semi-empirical saturation formulae, *e.g.*

$$\frac{R_v}{H_0} = \left(\frac{\pi}{2\beta}\right)^{1/2} \quad : \xi_0 \geq \xi_c \quad : \text{reflective} \quad (5a)$$

$$\frac{R_v}{H_0} = \frac{\xi_0^2}{\pi} \quad : \xi_0 < \xi_c \quad : \text{saturated} \quad (5b)$$

where β is the beach slope, R_v is the run-up height, normalised by H_0, the deep water wave height, L_0 is the deep water wavelength, and $\xi_c = |\pi^3/2\beta|^{1/4}$. The run-up height becomes independent of offshore wave height in saturated conditions. The above formulae, and others, were found to be consistent with the model predictions and observations. The model also predicted well the relative increase of reflected energy with increasing distance shoreward, and increasing ξ_0. Considerable differences were found in the run-up excursions measured by the wires of different heights, owing to the shape of the leading edge of the run-up tongue. The measured run-up excursions and mean superelevation were found to increase with decreasing wire elevation, and flow divergence caused

by continuous thinning of the run-up tongue sometimes resulted in onshore-directed near-bed velocities but offshore-directed velocities at 25cm above the bed.

JOHNSON and KOBAYASHI (1998) have developed a nonlinear time-averaged model of surf and swash-zone hydrodynamics which is more computationally efficient than traditional time-dependent models, and therefore more practical for studies of long term coastal morphology. The model extends the applicability of previous time-averaged models (*e.g.* BATTJES and STIVE, 1985; DALLY and DEAN, 1986) to the swash-zone. Various tests (KOBAYASHI *et al.,* 1997, 1998) have shown a considerable improvement over the earlier time-averaged models, especially in the inner surf and swash-zones.

SEDIMENT TRANSPORT IN THE SWASH-ZONE

Modes of Transport

The separation of sediment transport into bedload and suspended load has long been a source of difficulty in measuring cross-shore sediment transport in the surf-zone, due to the lack of suitable instrumentation for measuring bedload transport, poor theoretical knowledge and general observation difficulties. It is also a matter of some controversy whether the movement of sediment in the swash-zone should indeed be separated into these two modes (*e.g.* MASSELINK and HUGHES, 1998).

The distinction between bedload and suspended load has been defined in various different ways depending on the context. BAGNOLD (1956) defined bedload as that part which is supported by intergranular forces, and suspended load that part which is supported by fluid drag. However, a given grain may be supported by both mechanisms, which obviously creates measuring difficulties (NIELSEN, 1992).

The difficulty in measuring bedload transport has hampered the process of model development (HUNTLEY *et al.,* 1993), and, at the time of writing, a suitable standard high frequency measuring device for bedload is not yet in existence. Most attempts at measuring bedload have been made using traps (*e.g.* HARDISTY *et al.,* 1984; KAWATA *et al.,* 1990), although HARDISTY (1991) used hydrophones to monitor the self-generated noise produced by inter-particle collisions to estimate bedload transport. This technique is described in detail in JAGGER and HARDISTY (1991), and based on previous work by MILLARD (1976), THORNE *et al.* (1983, 1984, 1989), HEATHERSHAW and THORNE (1985) and THORNE (1985, 1986). The experiment was carried out on a beach containing gravel of about 10–12 mm diameter. Successful use of this technique on sand beaches has not been reported.

The relative importance of bedload transport compared with suspended load in the swash-zone was examined by HORN and MASON (1994). They used a trap containing compartments for bedload and suspended load. The division between the compartments was 1cm above the bed, which effectively meant that their definition of bedload was sediment moving below a height of 1 cm. Suspended load was therefore defined as any sediment moving above 1cm. The traps were installed in the mid-point of the swash-zone, and retained in place throughout half a wave cycle (uprush or backwash). The

relative weights of sediment caught in the traps were used to infer the relative importance of the two modes of transport. They concluded that, out of the four beaches studied, bedload transport was greater than suspended load on the backwash of three, and on both the uprush and backwash of two.

It has been suggested that the conventional separation into bedload and suspended load may be of little use in the swash-zone, and it may be more convenient to consider the total load (for which a model was proposed by BAILARD, 1981). It has been pointed out by HUGHES et al. (1997) that, in the swash-zone, high shear stresses dictate that the sediment transport will be predominantly sheet flow, which is similar to bedload but with the moving layer being several grain diameters thick, over a flat bed. This concept adds further complications and uncertainty to the problem of modelling sediment transport in the swash-zone, and it remains to be resolved which mode of transport will be best used to describe the sediment movement in this area.

Field Measurement of Swash-Zone Sediment Transport: General

Although there has been considerable investigation into swash-zone hydrodynamics, the number of field studies of swash sediment transport have been relatively few in number. Only very recently have advances in instrumentation allowed more promising measurements to be made.

Early field studies of swash-zone sediment transport concentrated on measuring changes in bed elevation of the foreshore during uprush-backwash cycles (e.g. DUNCAN, 1964; STRAHLER, 1966; WADDEL, 1973, 1976). Also, HOWD and HOLMAN (1984) have suggested that sediment level oscillations in the foreshore may be related to infragravity motions.

Field measurements of sediment transport in the swash-zone might be divided into two separate schools. (a) Low energy conditions, with steep beaches in the reflective end of the continuum. Here, incident waves tend to break very close to the shoreline, and transform directly into swash motions, i.e. incident frequency oscillations in shoreline position are directly related to wave heights beyond the break-point. (b) High energy conditions on relatively flat, dissipative beaches, where there is a wide surf-zone, and incident waves become saturated. Here there is a predominance of infragravity energy at the shoreline, and continuous measurements of suspended sediment concentration have been made using instruments such as the optical backscatter sensor (DOWNING et al., 1981).

Field Measurements On Steep, Reflective Beaches

In most of the studies described in this section, individual swash events have been monitored separately, and the sediment has been collected in traps. As opposed to measuring the instantaneous sediment flux, the total amount of sediment transported up or down the beach on the uprush or backwash respectively has been measured.

HARDISTY et al. (1984) measured uprush and backwash sediment load and cross-shore velocity on two relatively steep beaches in the UK. The velocity was estimated using the deflection of a 'swinging vane', and the sediment was collected in two bedload traps, one for uprush and one for backwash. The experiment was designed to calibrate a modified version of the Bagnold equations for bedload transport (BAGNOLD, 1963, 1966); i.e.

$$I_u = \frac{k_u U_u^3 T_u}{\tan \phi + \tan \beta} \qquad (6)$$

$$I_b = \frac{k_b U_b^3 T_b}{\tan \phi - \tan \beta} \qquad (7)$$

where the subscripts 'u' and 'b' are for uprush and backwash respectively, I is the total immersed weight of sediment transported during either the uprush or backwash phase of the swash cycle, U is the flow velocity, T is the uprush or backwash duration, ϕ is the angle of internal friction of the sediment, also known as the angle of repose or shear ($\tan\phi \approx 0.6$ for quartz sand), β is the beach slope. The calibration constant (k) is a factor which encompasses parameters which are difficult to measure such as bedload efficiency factor and friction factor (see MASSELINK and HUGHES, 1998). There appeared to be little difference in the derived values for the calibration constant for uprush and backwash, which seemed to suggest the denominator in equations 6 and 7 was compensating for the differences in upslope and downslope transport in the correct way. They also suggested that the value of k was likely to vary from beach to beach, with a possible dependence upon grain size (see HARDISTY, 1983).

The results of the above study were also used to examine a very simple equilibrium model, in which the ratio between the uprush and backwash transport was used to determine whether the beach was eroding or accreting. It was found that the transport was uprush dominated, indicating overall accretion throughout the experiment, and this was confirmed by comparing beach slopes.

YU et al. (1990) performed an experiment in the swash-zone in fairly low-energy conditions, on a beach in Norderney, Germany, to observe the characteristics of sheet-flow in the field. Sediment concentration changes in the sheet-flow layer were measured using a resistance type sheet-flow probe (RIBBERINK and AL-SALEM, 1992, 1995), and concentration changes were compared with flow velocities measured higher in the water-column. The intrusion depth of the sheet-flow layer itself was also measured, together with the local morphological changes throughout the experiment. A moving layer of sediment up to 8mm deep was found, which could be observed during periods of increased velocity, especially during the final stages of the backwash.

A recent field study in the swash-zone was carried out by HUGHES et al. (1997), on a steep beach with wave heights of about 0.5m. It was noted that the swash oscillations were occurring principally at incident wave frequencies. Measurements were taken on the uprush only, of (a) 'total' (bedload and suspended) sediment load using a sediment trap with an opening 50cm high by 10cm wide; (b) flow velocity using ducted-impeller type current meters, and (c) water level using a capacitance probe. It was acknowledged that certain errors would be inevitable from the flow meters, especially in shallow depths due to the water not completely covering the impeller. It was also pointed out that care must be taken to

avoid fouling due to seaweed and other debris, and also the tendency of the impeller to continue revolving after it dries out.

The total load of sediment transported during the uprush was noted for 35 swash 'events', and this was compared with the average total transport of sediment per uprush-backwash cycle, calculated from the morphological change of the beach throughout the experiment. It was found that the amount of sediment moved during each uprush was far greater than net movement during the whole uprush-backwash cycle, implying that the net transport per swash cycle is the relatively small difference between two large quantities.

The applicability of the modified Bagnold bedload equations (6 and 7) was also investigated for use in the swash-zone. The k value in equation 7 (uprush only) was found by regression analysis against the data. The value of k seemed to be much smaller than that obtained by HARDISTY et al. (1984), and this was attributed to either differences in grain size, or the inability of the swinging vane instrument used by HARDISTY et al. to respond to rapid changes in velocity (which would tend to underestimate the time-averaged velocity, and hence overestimate k). A calculation was also made based on the sheetflow criterion suggested by WILSON (1987) to confirm that sheetflow conditions were, in fact, predominant in this experiment.

A very similar experiment was performed by MASSELINK and HUGHES (1998), who monitored 27 swash events, with the sediment load of each event being correlated with both the uprush and backwash velocities. The sediment load was found to display a strong relationship with the velocity cubed. The constant of proportionality in both Bagnold and Shields type sediment transport models on the uprush was found to differ from that on the backwash. This was attributed to inherent differences between uprush and backwash processes such as accelerating versus decelerating flows, groundwater effects, and excess suspended sediment on the uprush due to bore collapse.

The results of the above studies highlight the importance of high concentrations of sediment moving low in the water column, which are still extremely difficult to measure. Uncertainties and sometimes conflicting results appear due to the different measurement techniques used. Further difficulties also arise in deploying fragile instruments such as the sheet-flow probe of YU et al. (1990) in high-energy conditions (see below).

Field Measurements on Dissipative Beaches

Advances in the design of non-obtrusive instrumentation which can be used very close to the bed have allowed measurements of instantaneous near-bed velocity and suspended sediment in the swash-zone to be made. These instruments have been developed directly from those used in the outer and inner surf-zone. However, very few measurements of this kind in the swash-zone have been made so far.

The optical backscatter sensor (OBS), originally designed for measuring suspended sediment in the surf-zone (DOWNING et al., 1981) may also be used in its original, or modified forms, to measure sediment concentrations in the swash-

zone. This instrument consists of an infra-red emitting diode and a silicon photo-voltaic cell (light detector). The OBS has been used successfully in the inner and outer surf-zone at vertical elevations as low as 5cm above the bed (e.g. DOWNING, 1984; JAFFE et al., 1984; STERNBERG et al., 1984; BEACH and STERNBERG, 1988; STERNBERG et al., 1989; GREENWOOD et al., 1990; BLACK and ROSENBERG, 1991; RUSSELL et al., 1991; VAN HARDENBERG et al., 1991; DAVIDSON et al., 1993). Note also that, using estuarine muds, KINEKE and STERNBERG (1992) have used the OBS to measure concentrations of up to 320g/l. To measure suspended sediment concentration close to the bed, attention has been paid to developing miniaturised versions of the OBS, to avoid the relatively large vertical cross-section of the probe causing scour from flow redirection (e.g. STERNBERG et al., 1984; BEACH et al., 1992).

The acoustic Döppler velocimeter (ADV) is becoming available in miniature form, suitable for measuring flow velocities in environments such as the swash-zone (KRAUS et al., 1994). It can simultaneously measure all three components of flow at sampling rates of up to 25Hz, thereby making it suitable for turbulence measurements. Recent tests have been carried out to evaluate the accuracy of this instrument (VOULGARIS et al., 1998), whereby simultaneous measurements were carried out using the ADV together with a laser Döppler velocimeter (LDV), in the same sampling volume. Using this technique, it was found that the ADV could measure the mean velocity to within 1% of the (much more accurate) LDV values.

If measurements of suspended sediment concentration are combined with those of cross-shore velocity in a similar way to the techniques used in the inner and outer surf-zone (e.g. HUNTLEY and HANES, 1987), then values of cross-shore suspended sediment fluxes may be obtained in the swash-zone. BEACH and STERNBERG (1991) used the FOBS (fibre-optic backscatter sensor) to measure suspended sediment concentration in the swash-zone of a highly dissipative beach in very high energy conditions, with offshore wave heights of several metres. An array of FOBS sensors was placed between 0.5cm and 5cm above the bed. Measurements of flow velocity were also taken using a single 4cm diameter impeller-type current meter. The sediment transport in the swash-zone was found to be highly infragravity dominated, with the largest sediment suspension 'events' at frequencies of 0.01 to 0.02Hz (50 to 100s period).

The vertical array of sensors also allowed the time-dependent vertical distribution of sediment to be analysed. It was found that, at the start of the uprush, the sediment concentrations were at a maximum, then tended to decrease rapidly as the uprush decelerated. On flow reversal to backwash, when the flow was accelerating, the sediment was suspended progressively higher in the water column and overall concentrations increased. Co-spectral analysis of the cross-shore velocity and sediment concentration measured by FOBS sensors at 2.8cm and 5cm, revealed considerable differences between the infragravity transport at the two different heights. At 5cm, the co-spectrum showed two large infragravity peaks of opposite sign, but similar magnitude, with the onshore-directed peak of a slightly higher frequency. At 2.8cm there
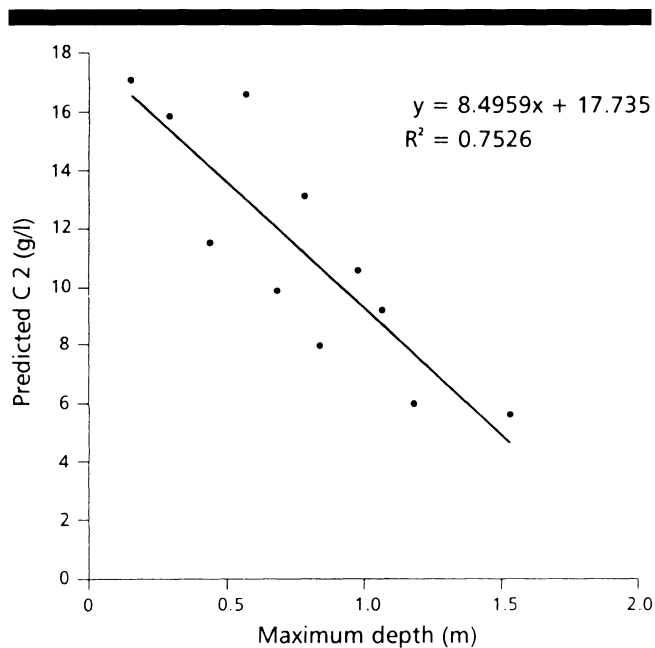
Figure 5. Predicted near-bed SSC at a reference height of 2 cm as a function of water depth (after OSBORNE and ROOKER, 1999). Note that, since the sensor height was not constant, the SSC at 2cm was predicted from a logarithmic profile.

raphy using the video method of HOLLAND and HOLMAN (1997). Their observations were used to develop and validate a very simple model of swash-zone sediment transport, using the measured shoreline change in conjunction with the hydrodynamic measurements. The model was found to be successful in making qualitative predictions of the shoreline morphodynamic evolution.

GROUNDWATER

One of the difficulties of describing and modelling the hydrodynamics and sediment transport in the swash-zone comes from the added complication of the flow of water into and out of the beach face, and the shape and position of the watertable relative to the swash-zone. A recent review of coastal groundwater dynamics were given by NIELSEN (1998) and an overview of measurement techniques and recent results is given by TURNER (1998).

The Watertable

The uprush-backwash cycle has been found to have direct effects upon the shape and position of the beach groundwater table, which could affect the hydrodynamics and sediment transport in the swash-zone by altering the degree of saturation of the beach face. The following section describes studies relating to the dynamics of the watertable and how it is linked with the swash cycle.

There has been much interest in improving the understanding of the behaviour of the beach watertable in terms of relatively long-period oscillations ranging from infragravity-frequency to seasonal fluctuations (e.g. ERICKSEN, 1970; HARRISON, 1972; LEWANDOWSKI and ZEIDLER, 1978; ELIOT and CLARKE, 1988; NIELSEN et al., 1988; NIELSEN, 1990; NIELSEN and KANG, 1995; TURNER et al., 1997). Somewhat fewer measurements have been made of incident frequency groundwater level oscillations (e.g. WADDELL, 1973, 1976, 1980; BRADSHAW, 1974, 1980; TURNER, 1995; TURNER and NIELSEN, 1997; LI et al., 1997). It was generally found that standing waves produced by reflection on a steep beach could translate low frequency motions to the water table, whereas the water table was less likely to respond directly to the incident waves. Hence it was suggested that the beach matrix acted as a low pass filter. HEGGE and MASSELINK (1991) compared run-up measurements taken using a run-up wire, with the time-varying response of the groundwater level measured with a piezometer, on a steep beach during incident-wave periods of between 10 and 20s (0.05–0.1Hz). It was found that the watertable seemed to act as a band pass filter, responding more readily to oscillations with frequencies around 0.013Hz (77s), than to those either side (see Figure 6). Despite this, incident frequency oscillations in the water table were detectable, and were closely related to swash oscillations. The response of the watertable also appeared to be asymmetrical, exhibiting a rapid-rise and slow fall, comparable with the observations of NIELSEN et al. (1988) at tidal frequencies.

A study of the moisture content below the bed of sandy beaches was performed on two contrasting beaches (a coarse grained, steep beach and a fine grained, dissipative beach)

was a single, very large infragravity peak, directed offshore. These transport differences between the two heights were attributed to a frequency-dependent velocity-concentration phase reversal (causing the transport to change direction), being associated with a time lag due to the vertical diffusion of sediment.

OSBORNE and ROOKER (1998, 1999) examined the hydrodynamics and sediment transport in the swash-zone and inner surf-zone of a high-energy dissipative beach. Near-bed velocities and turbulence were measured using an ADV, and suspended sediment concentration was measured using the OBS. In addition to findings which confirm those of previous workers (e.g. BEACH and STERNBERG, 1991), that concentrations of suspended sediment may be much higher in the swash-zone than those in the inner surf-zone, and that the temporal structure of the velocity and concentration was infragravity-dominated, it was also observed that very high suspended sediment concentrations were present in association with hydraulic jumps generated by the uprush interacting with the previous backwash. OSBORNE and ROOKER also found an inverse relation between averaged SSC and water depth (see Figure 5). This suggested that higher shear stresses were generated at the start and end of each swash event when water depths were small, and also that more sediment was suspended in the swash-zone than in the deeper water of the surf-zone.

HOLLAND et al. (1998) made a comprehensive set of measurements during the DUCK94 and SANDYDUCK experiments on a dissipative beach. Swash-zone measurements included cross-shore velocity using an ADV, and swash edge velocity and displacement together with 3D foreshore topog-
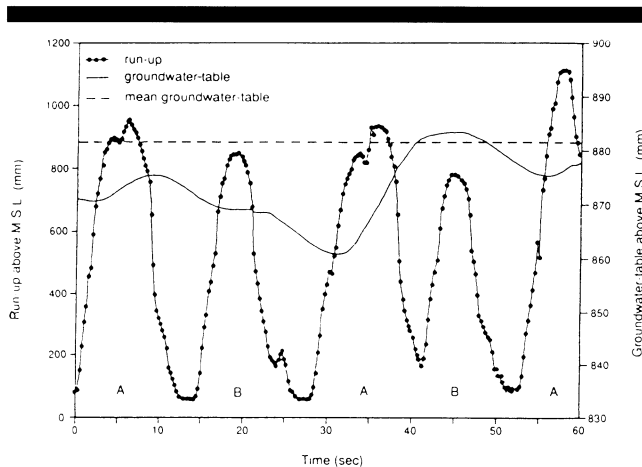
Figure 6. Comparison of time-series of run-up and groundwater levels. M.S.L. = mean sea level. (after HEGGE and MASSELINK, 1991)

by TURNER (1993). A neutron probe was used to measure shore-normal profiles of the moisture content between the watertable and the surface. The presence of a previously hypothesised saturated capillary fringe above the watertable was confirmed, which could explain the ability of the watertable to rise almost instantaneously upon addition of a thin layer of surface water such as that produced by a swash uprush (this is a well-known hydrological phenomenon known as the reverse Wieringermeer effect).

A model was developed by BAIRD and HORN (1996) to predict tide-induced variations in watertable elevations in sandy beaches, based on a one-dimensional form of the Boussinesq equation, *i.e:*

$$\frac{\partial h}{\partial t} = \frac{k}{s} \frac{\partial}{\partial x}\left(h\frac{\partial h}{\partial x}\right) \tag{8}$$

where h is the elevation of the watertable, t is time, k is the hydraulic conductivity of the beach sediment, s is the specific yield or drainable porosity, and x is the horizontal distance. See also BAIRD et al. (1998b). This model was field tested on a relatively low energy microtidal beach, using a shore normal transect of screened wells containing pressure transducers. It was found that the model was able to predict with some accuracy the changes in shore-normal profile of the watertable elevation over time, therefore providing a suitable boundary condition for swash infiltration and pressure propagation models (see also BAIRD et al., 1998a).

Infiltration-Exfiltration

One of the difficulties of describing and modelling the hydrodynamics and sediment transport in the swash-zone, is due to the vertical flow of water into and out of the beach face. Most of the studies described in the following section suggest that sediment transport on the backwash is enhanced by the process of infiltration-exfiltration, but it is still unclear whether this is always the case.

GRANT (1946, 1948) was one of the first to suggest a relation between groundwater and sediment movement in the

foreshore. The following mechanism was proposed: (a): On the uprush, if the beach is dry (*i.e.* the watertable is low), the uprush will infiltrate into the sand and hence slow down, causing greater deposition of the sediment suspended in the uprush. If the beach is wet (a high watertable), there will be less infiltration, hence less deceleration and therefore less deposition. (b): On the backwash, the outflow of groundwater causes fluidisation of the upper layer of sand, and hence augments offshore transport of sediment.

A model was developed by PACKWOOD (1983), based on the assumption that one of the major contributing factors to sediment transport on the foreshore is infiltration-exfiltration. The model was used to predict runup due to a single bore incident on an initially dry beach. He found that the amount of water percolating into the beach face increased with grain size, and for fine sand, the runup was almost the same as that on an impermeable slope. However, with medium sand, the greater porosity meant that there was a large amount of infiltration. This was seen to cause significant thinning of the swash 'lens' on the backwash, which would alter the ability of the flow to transport sediment. Packwood's conclusions were that, not only did grain size greatly affect the amount of infiltration, but that this effect was seen much more on the backwash than the uprush.

The effect of the permeability of a beach on the uprush-backwash cycle is illustrated in Figure 7. On a relatively impermeable beach (a) the sediment remains saturated throughout the uprush-backwash cycle and there is little infiltration. This effect would be enhanced by a previously elevated water table (from, say, a high tide). On a relatively permeable beach (b), water will sink into the beach face on the uprush, then flow seawards. This water may eventually emerge from the beach face at a point below the mean water surface.

TURNER (1995) developed a model to simulate the influence of groundwater seepage on the swash-zone sediment transport of macro-tidal beaches. The watertable exits the beach face at some point in the inter-tidal zone. As the swash-zone moves up and down the beach with the tide, the sediment transport will be influenced by the relative position of the watertable exit point. The model simulates the hydrodynamics in the uprush using the non-linear shallow water theory, and couples this to a Bagnold-type sediment transport model (BAGNOLD, 1963, 1966). However, due to difficulties in modelling the backwash, the beach slope was then used to parameterise the net transport of sediment over the whole uprush-backwash cycle. A possible explanation is also included of the slope break found in the intertidal zone of some macrotidal beaches. On the 'dry' upper portion of the zone, there is a greater degree of infiltration than on the 'wet' lower part. Hence on the upper part, the backwash is weakened, due to some of the water having been lost during the uprush. This suggests that net onshore transport is favoured in this region, causing the equilibrium beach-slope to be steeper. On the lower part, less water is lost from infiltration in the uprush, eventually leading to a less-steep equilibrium profile.

The equilibrium beach profile model of QUICK (1991) includes the effects of infiltration on the stresses imparted on the beach face sediment. During the uprush, the stresses in
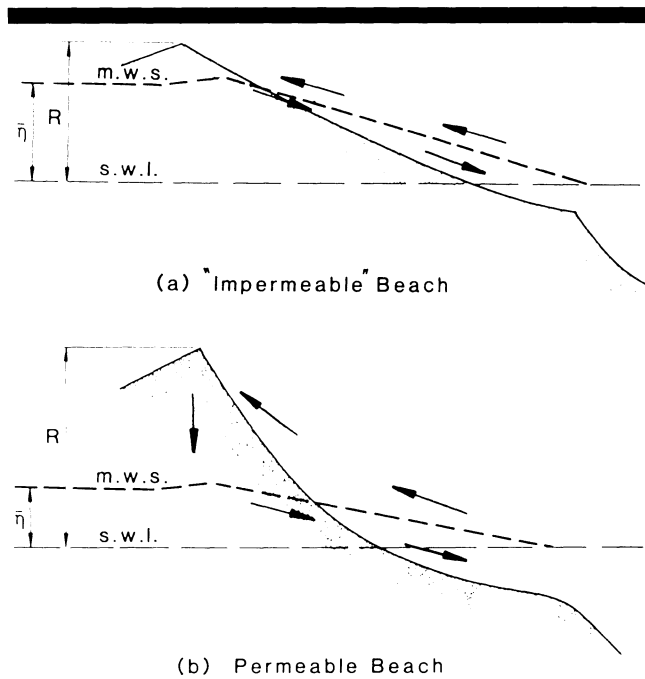
(a) "Impermeable" Beach

(b) Permeable Beach

Figure 7. Swash cycle on permeable and impermeable beaches. R = run-up; η = wave set-up; s.w.l = mean water surface; s.w.l. = still water level. (after GOURLAY, 1992)

the sediment increase due to the effects of infiltration; whilst on the backwash the hydraulic gradient associated with infiltration collapses and reverses, causing exfiltration. As the water emerges from the surface, the sediment is dragged into motion by the backrushing water.

A similar hypothesis was investigated by BAIRD et al. (1996). On the uprush the water pressure will propagate rapidly into the upper layers of the sediment; then on flow reversal to backwash, there will be a rapid decrease of pressure, producing forces acting vertically upwards just below the surface. This may lead to rapid groundwater outflow and hence fluidisation. They developed a model based on the three-dimensional form of equation 8, governing water movement through an isotropic and homogeneous saturated sediment; i.e:

$$\nabla^2 h = \frac{s}{k} \frac{\partial h}{\partial t} \qquad (9)$$

where h is the hydraulic head, s is the specific storage, t is time, and k is the hydraulic conductivity of the sediment. This model was then initially tested using a one-dimensional column of saturated sand, and some of the field data collected by HUGHES (1992). It was concluded that fluidisation is indeed likely to occur, especially in the latter stages of the backwash. The model also suggests that fluidisation of the bed occurs before the beach surface is exposed, increasing the likelihood of entrainment and seaward advection of sediment on the backwash.

Determining the magnitude of the pressure gradients just below the surface is critically important if the through-bed

flow behaviour is to be studied. HORN et al. (1998) conducted experiments to measure sub-surface pressure gradients in the swash-zone of a fine-grained microtidal beach using a method developed by BALDOCK and HOLMES (1996). They concluded that the pressure gradients are somewhat dependent upon the tidal stage. For example, on a rising tide they observed small positive pressure gradients on the uprush and large negative pressure gradients on the backwash; but on a falling tide, these differences did not occur.

TURNER and NIELSEN (1997) measured pore-pressure at three heights below the bed, using a vertical array of pressure sensors, in the swash-zone of a relatively flat beach, with wave heights of about 0.5m. By careful consideration of the groundwater dynamics in conjunction with their field results, they showed that rapid and relatively large upward fluctuations in the water table, due to the 'reverse Wieringermeer effect', can be caused by small amounts of downwards infiltration from swash uprush. These fluctuations are not actually associated with vertical flows of water into and out of the beach face, rather simply the displacement of a constant pressure surface. Therefore, only the physical movement of water due to pressure gradients beneath the bed can cause fluidisation.

If laminar flow is assumed, it is possible to calculate w, the instantaneous vertical flow of water through the beach face, from Darcy's law, i.e:

$$w = k\left(\frac{1}{\rho g}\frac{\partial p}{\partial z} - 1\right) \qquad (10)$$

where k is the hydraulic conductivity, ρ is the fluid density, and ∂p/∂z is the vertical pressure gradient. The critical fluidising velocity, w_c i.e. the vertically-upwards velocity at which bed fluidisation is possible, is also calculable if the weight of the sediment is balanced against the upward buoyancy force due to the pressure gradient, i.e:

$$\rho_s g V = \frac{w_c}{k}\rho V \qquad (11)$$

where V is volume and ρ_s is the sediment density. Hence,

$$w_c = k\left(\frac{\rho_s}{\rho} - 1\right) \qquad (12)$$

TURNER and NIELSEN (1997) found that, on their beach under study, vertical flow magnitudes were of the order of 10^{-4} m/s, whereas w_c for the grain size at their site was about 10^{-2} m/s, meaning fluidisation was unlikely. If the velocity of watertable rise were (mistakenly) taken to be associated with upwards flow of water, then this would have easily exceeded w_c and hence fluidisation might have been expected.

NIELSEN (1998) has derived a modified version of the Shields parameter to account for the effects of infiltration-exfiltration on sediment transport in the swash-zone. The two opposing effects are boundary layer modification (MARTIN, 1970) and stabilising-destabilising (NIELSEN, 1992). The former is parameterised in the numerator, and the latter in the denominator, therefore, the overall effect on the Shields parameter will depend on which process dominates, i.e.
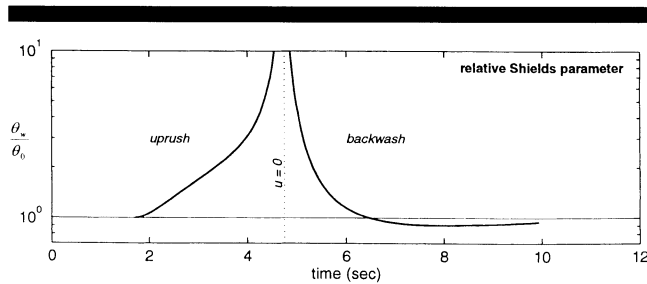
Figure 8. Relative Shields parameter over a simulated uprush-backwash cycle (after TURNER and MASSELINK, 1998). The u = 0 line indicates flow reversal between uprush and backwash.

$$\theta = \frac{u_*^2\left(1 - \alpha\dfrac{w}{u_*}\right)}{gd\left(s - 1 - 0.5\dfrac{w}{k}\right)} \qquad (13)$$

where u_* is the friction velocity, α is an empirical constant, and d is the median grain size. Nielsen hypothesised that quartz sands with d < 0.58mm are likely to be stabilised by infiltration (i.e. decreased transport on the uprush), whereas with larger grain sizes the boundary layer effects may start to become dominant, effectively increasing uprush transport.

TURNER and MASSELINK (1998) derived an alternative form for the modified numerator, which has been derived from work by MICKLEY et al. (1954), and CONLEY and INMAN (1994). The numerator, unlike Nielsen's, does not assume a linear relation between shear stress and infiltration velocity. The parameter was tested using pore-pressure data from a beach with d = 0.5mm, and modelled cross-shore velocities. It was found that the effect of boundary layer modification appeared to dominate, with the simulated peak transport rates increased by up to 40% on the uprush and reduced by 10% on the backwash. Figure 8 shows the relative Shields parameter (θ_w/θ_0) plotted against a simulated uprush-backwash cycle. The asymmetry of this plot shows that the combined effects of infiltration-exfiltration were more significant during uprush.

In summary, the processes acting below the bed in the swash-zone have been shown to be important in addition to those above the bed, and a more complete picture of the swash-zone will begin to emerge when more measurements are made of the hydrodynamics and sediment transport, concurrently with watertable elevations and sub-surface pore-pressure gradients.

CONCLUSIONS

This review summarises the recent literature on the hydrodynamics and sediment transport in the swash-zone of natural beaches. The importance of long wave motions in the inner surf-zone is well established, and recent work has also highlighted its importance in the swash-zone. The hydrodynamics of the swash-zone has been studied fairly comprehensively, and has been modelled with reasonable success in the

uprush, using modified forms of the non-linear shallow water equations.

However, sediment transport field measurements have been relatively few in number, mainly due to the lack of progress developing suitable instrumentation which can be used in this environment. It is required to measure sediment concentrations and flow velocities very close to the bed, in very shallow water, in a part of the beach which continually wets and dries, using instruments which cause the minimum amount of flow re-direction. Moreover, those conditions which produce the largest morphological changes, and therefore the most interesting and important results, happen to be the most challenging in which to measure.

Some of the most promising developments in instrumentation include the fibre-optic backscatter sensor (BEACH et al., 1992) for measuring suspended sediment concentration, and the acoustic Döppler velocimeter (VOULGARIS et al., 1998) for measuring velocity and turbulence.

There is also the added complication of extra processes governing onshore and offshore transport, which do not exist in the surf-zone, including groundwater influx and outflux. The idea of a thin fluidised layer of extremely dense sand/water mixture being formed on the backwash by the exfiltration of groundwater is being recognised as an important process (BAIRD et al., 1996). Attempts are being made to measure pore-pressure below the bed to investigate the above hypothesis.

Identification of the parameters to measure in the swash-zone depends to a certain extent upon our understanding of the physical processes involved. To establish the relative importance of the different processes will require the collection and careful analysis of more data. Only then will proper evaluation of swash-zone sediment transport models be achievable.

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☐ RESUMEN ☐

Se ha intentado relacionar las publicaciones recientes de la hidrodinámica y el transporte transversal de sedimentos en la zona de lavada, e identificar aspectos que necesitan más investigaciones. Hasta ahora, había relativamente pocos estudios en esta región, comparado con los de la zona de surf. Aunque había varios estudios de la hidrodinámica, la carencia de instrumentos significa que haya muy pocos del transporte de sedimentos. La estimación del transporte transversal total se ha sido dificil, porque esto es la diferencia entre dos cantidades relativamente grandes, que pueden contener errores de la misma magnitud que la diferencia. Además, hay complicaciones como el flujo vertical de agua dentro y fuera de la playa, lo que se esta empezando a estudiar recientemente. Antes de que podamos avanzar los módelos matemáticos, tenemos que entender mejor los procesos, con experimentos de gran escala, y decidir cuales parámetros son importantes, y cómo podriamos medirlos.