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The influence of swash infiltration–exfiltration on beach face sediment transport: onshore or offshore?

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Abstract

Measurements were obtained from the swash-zone of a high-energy macrotidal dissipative beach of pore-pressure at four levels below the bed, and cross-shore velocity at a single height above the bed. Time-series from relatively high ($H_s \approx 2.0$ m) energy conditions were chosen for analysis from the mid-swash-zone at high tide. Calculation of upwards-directed pore-pressure gradients shows that, in this case, fluidisation of the upper layer of sediment, leading to enhanced backwash transport, is unlikely. An apparent conflict exists in the literature regarding the net effect of infiltration–exfiltration on the sediment transport, through the combined effects of stabilisation–destabilisation and boundary layer modification. This is examined for the data collected using a modified Shields parameter. Inferred instantaneous transport rates integrated over a single swash cycle show a decrease in uprush transport of 10.5% and an increase in backwash transport of 4.5%. Sensitivity tests suggest that there is a critical grain size at which the influence of infiltration–exfiltration changes from offshore to onshore. The exact value of this grain size is highly sensitive to the method used to estimate the friction factor. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Backwash; Infiltration; Pore-pressure; Sediment; Swash; Uprush

1. Introduction

One of the factors which may need to be taken into consideration for sediment transport in the swash-zone is the vertical flow of water into and out of the bed, and its effect on sediment mobility.

In the past, the effect of infiltration on sediment transport in the swash-zone has been assumed to be mainly connected with the percolation of water into the beach face, and hence the reduction of volume on the backwash (e.g. Grant, 1946, 1948; Emery and Gale, 1951; Duncan, 1964; Waddell, 1976). However, on fine to medium sand beaches, this mechanism is likely to be relatively unimportant compared with coarse sand or shingle.

It has more recently been hypothesised that fluidisation of the upper layer of sediment may occur due to rapid outflow of water from the beach face caused by sub-surface pressure forces acting vertically up-

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wards on the backwash (Quick, 1991; Baird et al., 1996; Horn et al., 1998). On the uprush, the water pressure will propagate rapidly into the upper layers of the sediment; then on flow reversal to backwash and subsequent reduction in swash depth, there will be a rapid decrease of pore-pressure, producing forces acting vertically upwards just below the surface. This may lead to rapid groundwater outflow and hence fluidisation. If the upper layers of sediment become fluidised, then this might considerably increase the sediment transport since the fluidised layer would quickly become entrained by the seaward flow in the backwash. This hypothesis was tested using a model by Baird et al. (1996), who concluded that fluidisation may occur, especially in the latter stages of the backwash.

Even if the upwards-directed pressure gradients are too small to produce fluidisation, they may still increase sediment transport on the backwash by reducing the effective weight of the sediment (i.e. 'destabilise' the bed). Conversely, downwards-directed pressure gradients on the uprush will increase the effective weight of sediment (i.e. bed stabilisation), thereby decreasing the potential for sediment transport (Hughes et al., 1998; Nielsen, 1998). Therefore, the net effect of the stabilisation–destabilisation process would be to bias the transport in the offshore direction.

Another mechanism which may have the opposite effect is the altering of the thickness of the boundary layer due to vertical flow into and out of the beach face. This was investigated in the laboratory by Conley and Inman (1994), albeit outside the breakpoint. They confirmed that the thickness of the boundary layer is reduced by infiltration and increased by exfiltration, therefore making the near-bed velocity relatively greater during infiltration. The turbulent vortices during infiltration are maintained

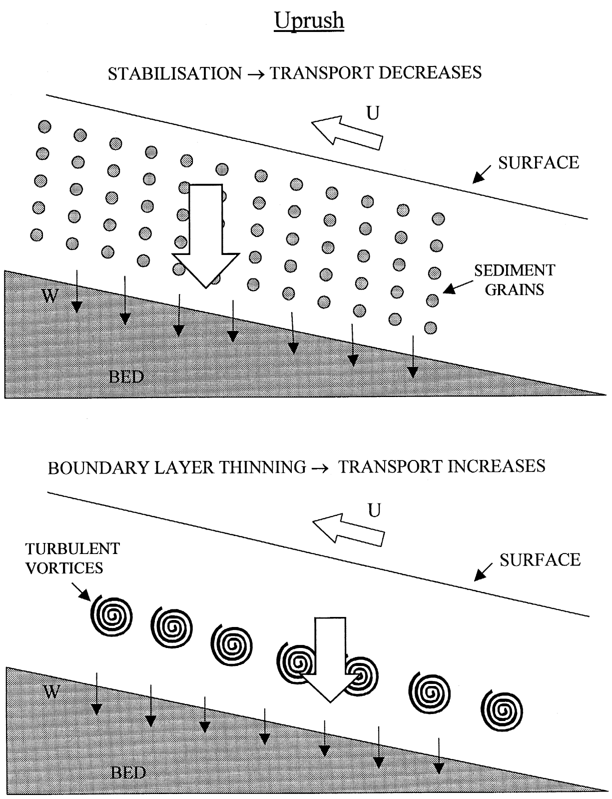

Fig. 1. Schematic representation of sediment stabilisation (top panel) and boundary layer thinning (bottom panel) due to infiltration on the uprush.

closer to the bed, thereby increasing the potential for sediment transport. During exfiltration, the turbulent vortices are elevated further from the bed, effectively thickening the boundary layer and decreasing the potential for sediment transport. In the swash-zone, this process would tend to enhance uprush transport and decrease backwash transport, i.e. bias the net transport onshore. Schematic illustrations of the two processes above are shown in Figs. 1 and 2.

The balance between the two processes of bed stabilisation–destabilisation and boundary layer modification has been quantified by Nielsen (1998) and Turner and Masselink (1998) (hereafter referred to as TM98), by defining a modified Shields parameter. On the uprush, the numerator increases with decreasing w (upwards through-bed flow velocity), to account for the increased shear stress due to boundary layer thinning, and the denominator also increases with decreasing w, to account for the stabilisation brought about by infiltration. On the backwash, both the numerator and denominator decrease with increasing w to account for boundary layer thickening and destabilisation from exfiltration.

Nielsen (1998) hypothesised that quartz sands with a median grain size (d_{50}) of about 0.58 mm 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.

The numerator of TM98, unlike Nielsen's, did not assume a linear relation between shear stress and infiltration velocity. They tested the modified Shields parameter using pore-pressure data from a beach with $d_{50} = 0.5$ mm. Cross-shore velocities were obtained using a model. It was found that the effect of boundary layer modification appeared to dominate, with increased uprush transport and reduced backwash transport.

The purpose of this paper is to examine subsurface pore-pressures and cross-shore velocities col-

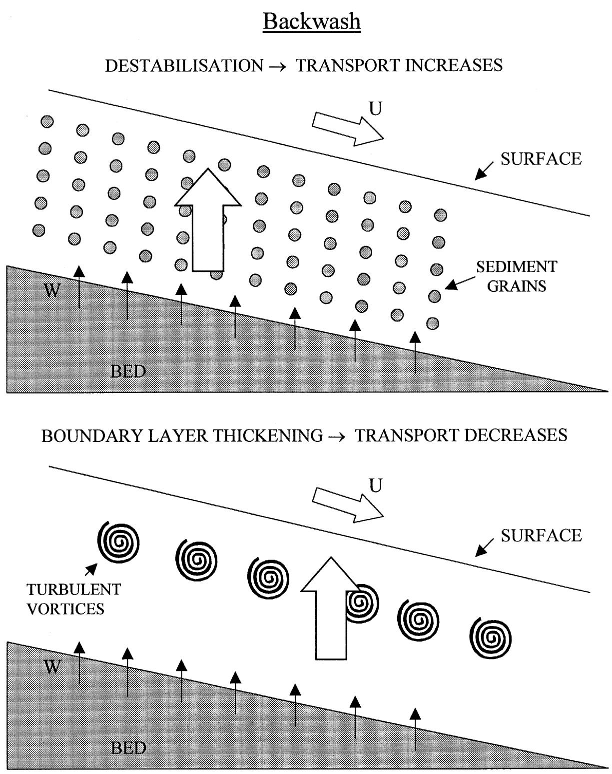

Fig. 2. Schematic representation of sediment destabilisation (top panel) and boundary layer thickening (bottom panel) due to exfiltration on the backwash.

lected from the swash-zone of a natural beach, as a step towards improving the understanding of how infiltration–exfiltration influences the sediment transport in the swash-zone.

The question of whether fluidisation is likely to be an important factor is still unclear. Therefore, a useful step is to investigate, using pore-pressure gradients, whether fluidisation was likely during the present study.

The apparently conflicting results of TM98 and Nielsen (1998) suggest that more study is required of the relative effects of the two processes which combine to cause a net onshore or offshore transport influence. The modified Shields parameter, together with the measured velocities, is used to assess which process was dominant during the present study. A representative swash event, obtained from ensembles of seven swash events from the data, is examined in detail.

Finally, some sensitivity tests are performed which attempt to identify the most important factors in determining which process will dominate under various different conditions. The equations derived contain some parameters (e.g. friction factor) which are difficult to estimate, and tests are done to assess the relative sensitivity of the results to changes in these parameters.

2. Field experiment

The data used in the present study were obtained from a field experiment performed at Perranporth Beach, UK during March 1998 (Butt and Russell, 1999). The field site is shown in Fig. 3. Perranporth is a macrotidal dissipative beach with a mean tidal range of 5.25 m. Significant wave height and period (H_s and T_s) during the experiment were 2.0 m and 8 s, respectively. The conditions were infragravity-dominated, with a broad-banded incident wave-field which contained a mixture of swell and wind-waves. The average beach slope (β) 20 m either side of the instrument rig position was 0.82° (i.e. $\tan\beta =$ 0.0143). The beach was linear and there was an absence of along-shore variations in topography. Sediment samples taken from the study site indicated the median grain size (d_{50}) to be 0.24 mm.

The measurements presented here are of cross-shore velocity within the swash zone and sub-surface pore-pressure. Velocity was measured using a miniature electromagnetic current meter with a 2-cm diameter discus head, manufactured by Valeport, UK. The instrument was mounted nominally at 5 cm above the bed. The minimum sensing volume of the discus-type head is recommended by the manufacturers as being a cylinder of the same diameter as the sensor, projecting from its face by half its diameter. In other words, the sensing face of the 2 cm head must be placed at least 1 cm from any solid object (in this case, the sea bed). Previous trials revealed that the approximate accuracy of these current meters is about ±8% (Butt, 1999).

Pore-pressure was measured at distances of 2, 5, 9 and 13 cm below the bed. The miniature pressure transducers were Druck PDCR830. These instruments had also been used for previous measurements of pore-pressure in the swash-zone (Baird et al., 1998). Published accuracy of the pressure transducers (combined non-linearity, hysteresis and repeatability) is ±0.1%. The transducers were covered in a Terram geotextile shroud to prevent the impingement of sand grains that could alter the output. Great care had to be taken to ensure the transducers were vertically aligned to avoid any horizontal pressure gradients from being mistaken for vertical gradients.

The data analysed are from a 17-min time series, recorded on 26 March 1998. Because of the considerable tidal range at this site, to obtain maximum stationarity in the data, and to minimise any direct effects of cross-shore tidal velocities, the time-series were recorded over high-tide slack water.

The instruments were located in the mid swash-zone (approximately half way between the run-up limit and the run-down limit), and so were periodically submerged. The data were sampled at 18 Hz, then block averaged at 2 Hz. Note that the pressure measurements presented are in hPa, where 1 hPa is hydrostatically equivalent to 1 cm head of water.

3. Pore-pressure gradients and potential fluidisation

The hypothesis that fluidisation of the upper layers of the bed might be a significant contributing factor for sediment transport on the backwash (e.g.

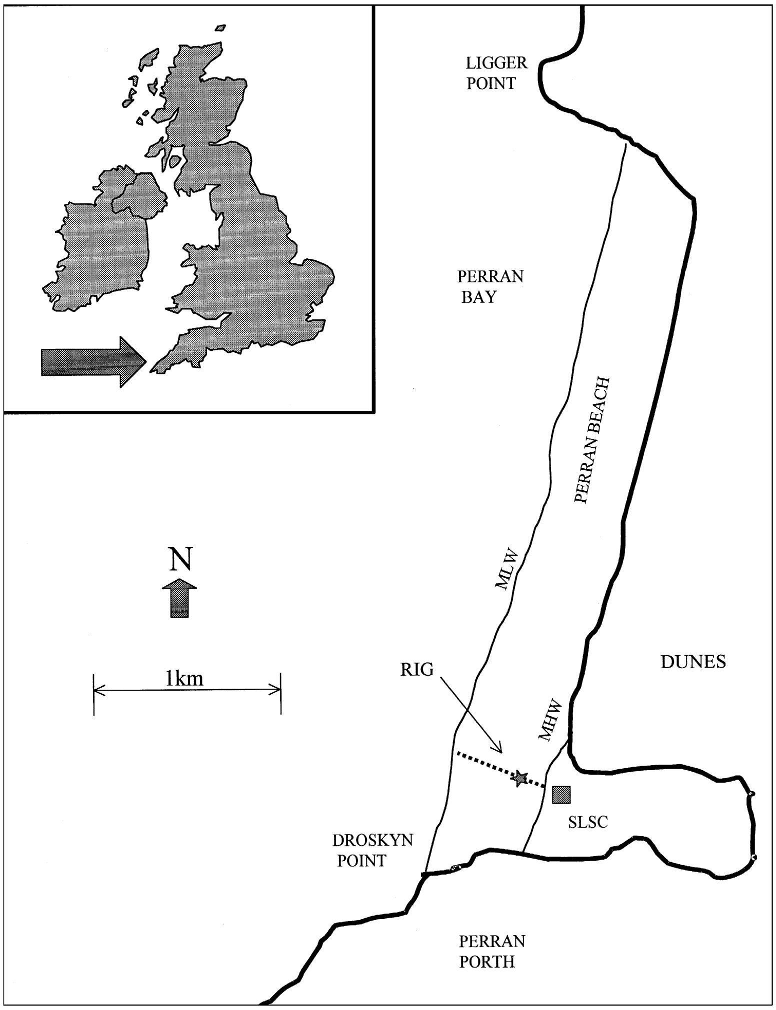

Fig. 3. Location of Perranporth.

Baird et al., 1996) may be investigated using the data collected in the present study.

Following TM98 (their Eqs. 12 to 17), it may be shown that the condition for fluidisation is given by:

$$\frac{w}{K} \geq \frac{(s-1)}{a} \qquad (1)$$

where w is the vertical fluid velocity in the bed (positive upwards), K is the hydraulic conductivity [m s^{-1}], $s = \rho_s / \rho$ is the specific gravity of the sediment, where ρ and ρ_s are the fluid and sediment densities, respectively, and a is the ratio between the seepage force acting in the surficial layers of sediment and that acting within the bed (Martin, 1970). Using a series of slope instability tests, Martin and Aral (1971) experimentally determined that the seepage force in the top layer of sediment particles is approximately half that within the bed. Hence, $a \approx 0.5$. Therefore, the condition for fluidisation is given by:

$$\frac{w}{K} \geq 2(s-1). \qquad (2)$$

If the water density is taken as 1025 kg m^{-3} and the sediment density as 2650 kg m^{-3} (for quartz), then fluidisation will occur if w/K exceeds about 3.2.

To obtain values for w/K in the present study, the assumption is made that the flow is Darcian, therefore:

$$\frac{w}{K} = -\frac{\partial h}{\partial z} \tag{3}$$

where h is the hydraulic head in cm (1 cm ≡ 1 hPa), and z is the vertical distance between sensors.

Fig. 4 shows time-series of (a) cross-shore velocity, (b) pore-pressure difference between the top and bottom sensors minus the hydrostatic pressure, (c) w/K calculated from Eq. (3) above, and (d) pore-pressure at 2, 5, 9 and 13 cm below the bed.

Note that, for all subsequent analysis in the paper, the pore-pressure gradient between the top and bottom sensors is used. Sensors used in Turner and

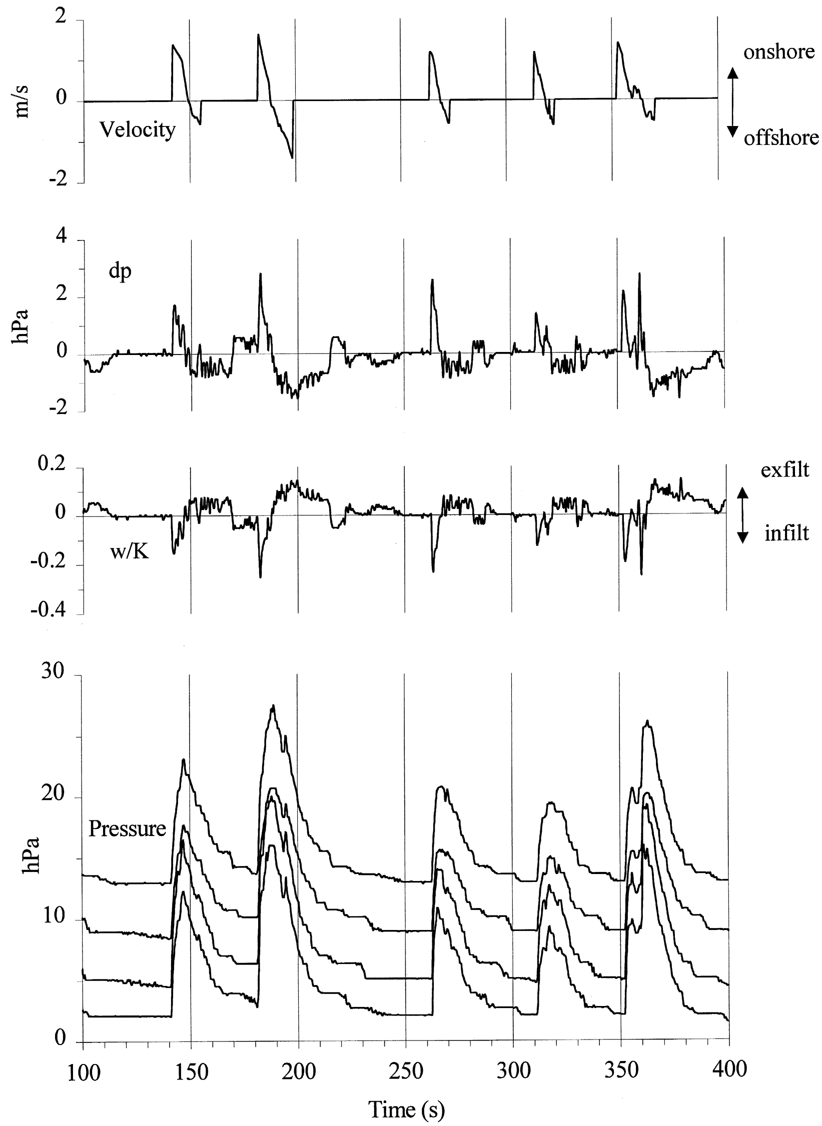

Fig. 4. Representative time-series of cross-shore velocity, pressure difference between top and bottom sensors, w/K, and sub-surface pore-pressures. The lowest pore-pressure trace corresponds to the transducer nearest the bed. Pressures are gauge, i.e. zero corresponds to atmospheric. 1 hPa ≡ 1 cm head of water.

Nielsen (1997) and TM98 were placed approximately 1 and 16 cm below the surface. Therefore, the top and bottom sensors were selected for the present study to allow comparison with the results of the previous two studies.

In Fig. 4, large, short duration, downwards-directed pore pressure gradients can be seen on the uprush, and longer duration upwards pressure gradients on the backwash. These pore-pressure gradients within the bed coincide with the variation in swash depth, which is the driving force for through-bed vertical flow. The values of w/K only reach about 0.2, so fluidisation is unlikely in this case.

4. Revised Shields parameters

The Shields parameter, θ (Shields, 1936), expresses the ratio between the disturbing and stabilising forces on sediment at the bed:

$$\theta = \frac{\tau}{\rho g d(s-1)} \tag{4}$$

where τ is the bed shear stress, ρ is the fluid density, d is the median grain size, and $s = \rho_s/\rho$ is the specific gravity of the sediment, where ρ_s is the sediment density. For the purposes of the present study, the denominator may be simplified to W, the immersed sediment weight per unit area. Hence, using the suffix '0' for the specific case of no through-bed flow:

$$\theta_0 = \frac{\tau_0}{W_0}. \tag{5}$$

To quantify the effects of infiltration–exfiltration, modifications to the numerator and denominator of this equation have recently been made by Nielsen (1998) and TM98, i.e.:

$$\theta_w = \frac{\tau_w}{W_w} \tag{6}$$

where the suffix w means that this parameter contains extra terms to account for through-bed flow.

The two opposing effects of infiltration–exfiltration may be quantified using Eq. (6). For example, on the uprush, when there is infiltration, the numerator will increase due to the thinning of the boundary layer but the denominator will also increase due to the extra stabilisation imparted on the sediment grains. On the backwash, when there is exfiltration, the numerator decreases due to the thickening of the boundary layer but denominator will also decrease due to destabilisation. Therefore, the Shields parameter will have a net increase or decrease according to the balance between the two opposing processes.

A simple and well-proven model for sediment transport (e.g. Meyer-Peter and Müller, 1948) is one in which the dimensionless sediment transport rate is proportional to $\theta^{3/2}$, i.e. $Q \propto \theta^{3/2}$, where Q is the dimensionless transport. This reduces to a 'velocity-cubed' dependence analogous to the energetics approach (Bailard, 1981), and as applied in the surf-zone by Russell and Huntley (1999). Hence:

$$Q_w = \left(\frac{\tau_w}{W_w}\right)^{3/2} \tag{7}$$

and

$$Q_0 = \left(\frac{\tau_0}{W_0}\right)^{3/2} \tag{8}$$

The difference between Eqs. (7) and (8) will isolate that part of the dimensionless sediment transport due to infiltration–exfiltration, and therefore give a simple indication of whether infiltration–exfiltration effects are biasing the sediment transport one way or another:

$$Q_{\mathrm{Infilt}} = Q_w - Q_0 \tag{9}$$

i.e.:

$$Q_{\mathrm{Infilt}} = \frac{u}{|u|}\left[\left(\frac{\tau_w}{W_w}\right)^{3/2} - \left(\frac{\tau_0}{W_0}\right)^{3/2}\right]. \tag{10}$$

The right-hand-side of Eq. (10) is multiplied by $u/|u|$ to preserve the net direction of potential sediment transport. For example, if the total transport (including that due to infiltration–exfiltration) is greater than the transport without infiltration–exfiltration, the effect of Q_{infilt} will be to increase the sediment transport in the direction of the flow. If this happens during the uprush, then the dominant process will be boundary layer thinning, but if it hap-

Table 1
Various solutions of Eq. (10)

$u/\|u\|$	Flow direction	Balance of terms inside bracket	Q_{infilt}	Dominant process
+1	onshore	term1 > term2	+ve (onshore)	boundary layer thinning
+1	onshore	term1 < term2	−ve (offshore)	stabilisation
−1	offshore	term1 > term2	−ve (offshore)	destabilisation
−1	offshore	term1 < term2	+ve (onshore)	boundary layer thickening

pens during the backwash, then the dominant process will be destabilisation. The four basic scenarios are illustrated in Table 1.

5. Derivations of the modified Shields parameter

The immersed sediment weight per unit volume of the bed (W) may be adjusted for infiltration–exfiltration by simply adding the weight loss or gain caused by seepage to the denominator of Eq. (4) (note that the vertical velocity (w) is positive upwards):

$$W_w = \rho g d(s-1) - 0.5\rho g d \frac{w}{K}$$

i.e.:

$$W_w = \rho g d\left(s - 1 - 0.5\frac{w}{K}\right). \tag{11}$$

To modify the numerator, Nielsen (1998) hypothesised a linear relation between shear stress (τ) and the relative vertical velocity (w/u). Based on this assumption, the following may be defined:

$$\tau_w = \tau_0\left(1 - \alpha\frac{w}{u} f^{-1/2}\right) \tag{12}$$

where f is a friction factor and α is an empirical constant.

TM98 have derived an alternative form for the modified numerator, which was based on the 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 modified shear stress may be defined as follows:

$$\tau_w = \tau_0\left(\frac{\Phi}{e^{\Phi} - 1}\right) \tag{13}$$

where:

$$\Phi = \frac{c}{f}\frac{w}{|u|} \tag{14}$$

where c is an empirical constant, which is about 2.0 for quasi-steady flow (Mickley et al., 1954), and f is the friction factor.

Using the quadratic stress law, i.e.:

$$\tau = 0.125\rho f u^2 \tag{15}$$

and Eqs. (10)–(14), an expression for the relative sediment transport due to the effects of infiltration–exfiltration (Q_{infilt}) is given by:

$$Q_{Infilt} = u^3\left(\frac{f\left(1 - \alpha\frac{w}{u} f^{-1/2}\right)}{8gd(s - 1 - 0.5w/K)}\right)^{3/2} - u^3\left(\frac{f}{8gd(s-1)}\right)^{3/2} \tag{16}$$

or:

$$Q_{Infilt} = u^3\left(\frac{f\Phi/(e^{\Phi} - 1)}{8gd(s - 1 - 0.5w/K)}\right)^{3/2} - u^3\left(\frac{f}{8gd(s-1)}\right)^{3/2}. \tag{17}$$

Note that it is unnecessary to multiply the right hand side by $u/|u|$ to preserve the direction of transport. This is clarified by taking u^3 outside the brackets.

6. Quantification of transport modification from infiltration–exfiltration

Before Eq. (16) or (17) can be applied, the values of various parameters must be determined. For quartz sand in water, $s \approx 2.6$. With a knowledge of the hydraulic conductivity (K), a value for w may be obtained from Eq. (3). To obtain a value for K, the empirical formulation of Bear (1972) is used, i.e.:

$$K = \left(\frac{\rho g}{\mu}\right)\frac{n^3}{(n-1)^2}\left(\frac{d^2}{180}\right) \quad (18)$$

where ρ is water density, $\mu \approx 10^{-3}$ N s m^{-2} (Williams and Elder, 1996) is the dynamic viscosity, $n \approx 0.45$ is the porosity (Dyer, 1986) and $d = d_{50}$ the median grain size. For the grain size of 0.24 mm in the present study, K is estimated to be of the order of 0.001 m s^{-1}.

The friction factor (f) is estimated using a formula for steady flow, since it is preferred to treat the flow in the swash-zone as quasi-steady, and the use of a formula for orbital flow (e.g. Swart, 1974; Wilson, 1989), is considered inappropriate (c.f. TM98; see also below).

The friction factor is often estimated by combining various basic equations relating to the boundary layer (e.g. Hughes, 1995). The von Karmen–Prantl equation ('law of the wall') gives the velocity profile in the boundary layer:

$$\frac{u(z)}{u_*} = \frac{1}{\kappa}\ln\left(\frac{z}{z_0}\right) \quad (19)$$

where $u(z)$ is the velocity at height z above the bed; u_* is the friction velocity where $u_*^2 = \tau/\rho$; $\kappa \approx 0.4$ is the von Karman constant, and z_0 is the roughness length of the bed. If the depth-averaged velocity is assumed to occur where $z = h/e \approx 0.37h$, and the roughness length is approximately $k/30$ where h is the water depth and k is the Nikuradse effective bed roughness (van Rijn, 1993), then Eq. (19) may be written as:

$$\frac{\bar{u}}{u_*} = 2.5\ln\left(11\frac{h}{k}\right). \quad (20)$$

Combining Eq. (15) with Eq. (20):

$$f = 1.28\left(\ln\left(11\frac{h}{k}\right)\right)^{-2}. \quad (21)$$

To obtain a value for k, it will be assumed that the bed is approximately flat, and any bedforms are negligible. Van Rijn (1982) reasoned that the grain roughness (k) presented to the flow is related to the grain size, and proposed:

$$k \approx 6d_{50}. \quad (22)$$

Therefore, for a particular grain size, the friction factor becomes a function of the water depth, i.e. it is time-dependent.

Eq. (16) contains the empirical constant α for which a suitable value is presently unknown (P. Nielsen, pers. comm, 1998). The sensitivity of the equation to this parameter is quite low (the value of α was arbitrarily varied over three orders of magnitude and the average and maximum values of Q_{infilt} were only found to vary by 1.14% and 3.1%, respectively). However, it is still preferred to use Eq. (17), whose numerator is also able to take into account the possible non-linear relation between shear stress and velocity (Conley and Inman, 1994).

Fig. 5 shows a representative section of the time-series of Q_{infilt} calculated from Eq. (17). Also shown for comparison are the cross-shore velocity (u), upwards velocity (w), and the no through-bed flow equivalent transport (Q_0).

Both on the uprush and backwash, the effects of infiltration–exfiltration appear to be biasing the potential sediment transport towards the offshore. This means that, on the uprush, the stabilising effect is dominating over boundary layer thinning, and on the backwash, destabilising is dominating over boundary layer thickening. This finding appears to contradict the results of TM98, which showed the opposite trend that modified boundary layer effects were dominant for the simulated swash cycle.

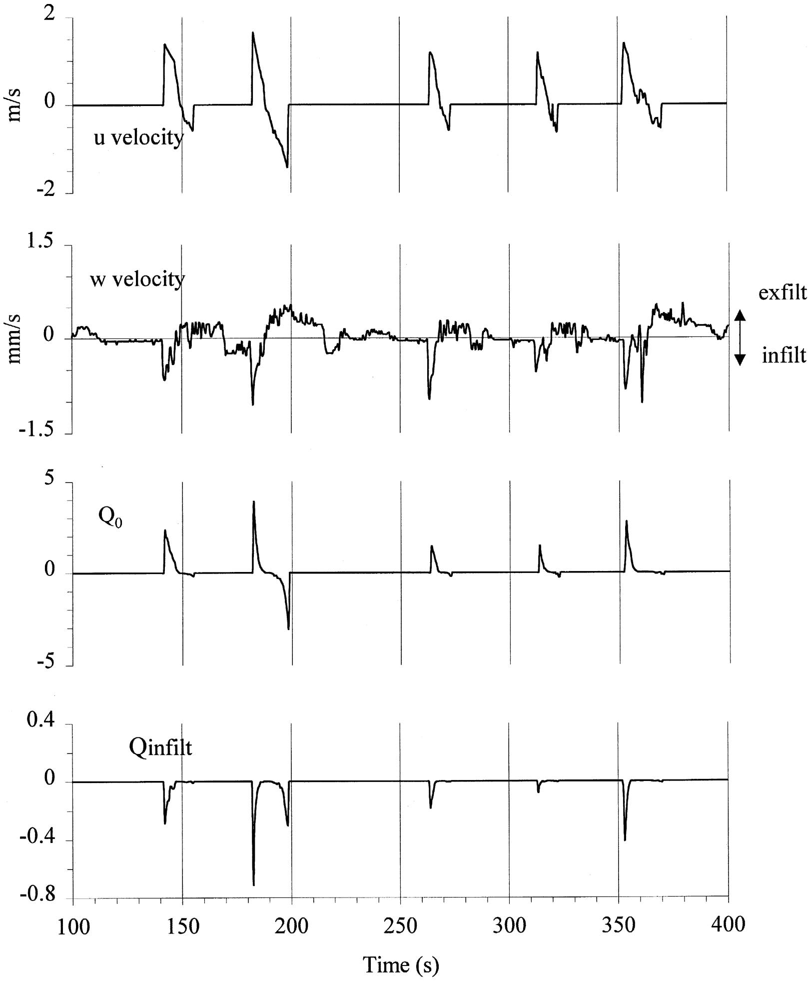

Fig. 5. Representative time series of cross-shore velocity, vertical velocity (positive upwards), dimensionless sediment transport without infiltration–exfiltration (Q_0) and dimensionless transport solely due to infiltration–exfiltration effects (Q_{infilt}) calculated from Eq. (17).

A time-series of cross-shore velocity and subsurface pore-pressure for a single infragravity swash cycle ($T \approx 40$ s) were obtained by taking an ensemble of seven swash 'events' from the entire time-series. Since each 'event' was not of the same duration, the time scale had to be normalised to the event duration. To illustrate the effects of infiltration–exfiltration over a single swash cycle, Eq. (17) was then computed using the ensembled swash events. A comparison of Q_0 and Q_{w} computed from the separate terms in Eq. (17), together with Q_{infilt} are shown over the ensembled swash cycle (see Fig. 6). Here, decrease in transport on the uprush and the (smaller) increase in transport on the backwash can clearly be seen.

A useful exercise is to obtain the total amount of sediment transported over the uprush and backwash by integrating under the curves in Fig. 6, and then calculating the difference due to infiltration–exfiltration. This provides useful insight to the net effect of infiltration–exfiltration integrated over the entire swash cycle.

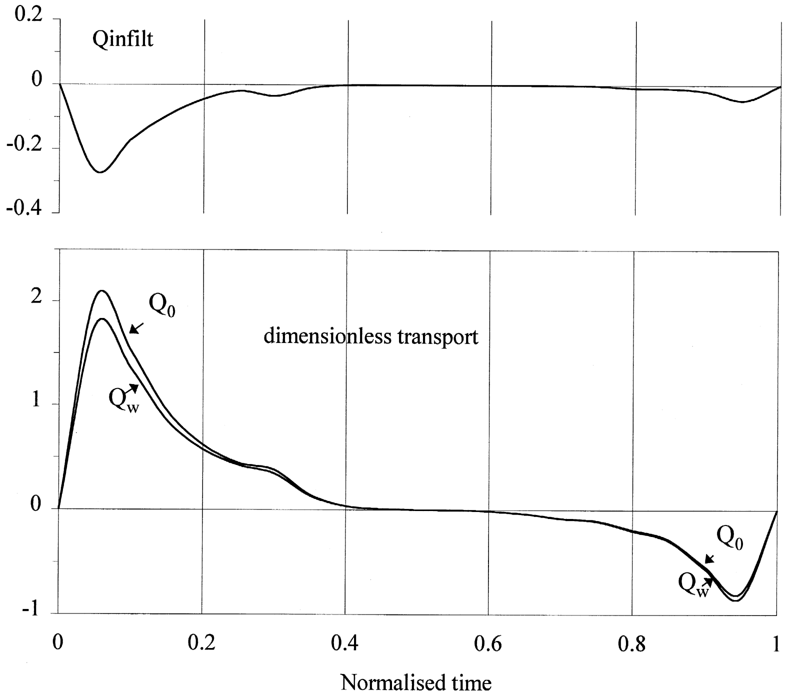

Fig. 6. Comparison of transport with (Q_w) and without (Q_0) infiltration–exfiltration over a single swash cycle, taken from the ensembles of individual swash cycles in the time-series. Top panel (Q_{infilt}) is the transport solely due to the effects of infiltration–exfiltration.

The total sediment transported without taking infiltration–exfiltration into account (S_0) is given by: For the uprush:

$$S_0(\text{uprush}) = \int_{t=0}^{t=0.5} (Q_0)\mathrm{d}t \tag{23}$$

and for the backwash:

$$S_0(\text{backwash}) = \int_{t=0.5}^{t=1} (Q_0)\mathrm{d}t. \tag{24}$$

Taking infiltration–exfiltration into account, the total sediment transported (S_w) is given by:

For the uprush:

$$S_w(\text{uprush}) = \int_{t=0}^{t=0.5} (Q_w)\mathrm{d}t \tag{25}$$

and for the backwash:

$$S_w(\text{backwash}) = \int_{t=0.5}^{t=1} (Q_w)\mathrm{d}t. \tag{26}$$

Since both the instantaneous transport and time are dimensionless, then S_0 and S_w have no physical units, and are used for comparison only. The most useful parameter here is the ratio between S_w and S_0 for the uprush, and the same ratio for the backwash. This gives an indication of the bulk effect of infiltration–exfiltration over the uprush and over the backwash. From the ensembled swash cycles (see Fig. 6), simple finite difference integration gives S_w/S_0 (uprush) = 0.895 and S_w/S_0 (backwash) = 1.045.

This means that, from the data collected in the present study, infiltration–exfiltration is likely to decrease the total amount of sediment moved upslope on the uprush by about 10.5%, and increase the total amount of sediment moved downslope on the backwash by about 4.5%.

7. Sensitivity tests

The study of TM98 concluded that there was a dominance of boundary layer modification over stabilisation–destabilisation. As a result, they asserted that the role of infiltration–exfiltration in the swash-zone is generally to enhance uprush transport. This appears to conflict with the results of the present study. Potentially important differences in theoretical approach and experimental conditions between the two studies are the following.

- In the present study, the cross-shore velocity was measured at the field site. TM98 only measured sub-surface pore pressures: the cross-shore velocity was predicted using a model.
- The median grain size (d_{50}) at Perranporth was 0.24 mm, whereas at Duck, USA (TM98), it was 0.5 mm.
- TM98 used a friction factor calculation after Wilson (1989), which was originally designed for oscillatory flow. However, they acknowledge that the flows in the swash-zone are quasi-unidirectional since the constant (c) in the non-linear relation between τ and w/u is assumed to be 2.0 rather than 0.9 for oscillatory flow. In the present study, the friction factor was calculated from a formula for steady flow, and varied with water depth. The friction factor in TM98 was assumed to remain constant at 0.01.

It would therefore seem appropriate to examine the sensitivity of the calculations made in the present study, to various parameters. In other words, if certain parameters were allowed to vary, could the balance of transport due to infiltration–exfiltration be made to change from offshore to onshore?

An interesting exercise is to examine the dependency of grain size on the balance between the two processes. Nielsen (1998) suggested that boundary layer effects are only likely to dominate at grain sizes above about $d_{50} = 0.58$ mm.

To assess the effect of grain size, the average value of Q_{infilt} over the whole time-series, $\langle Q_{\text{infilt}} \rangle$, was calculated from Eq. (17), which was then repeated while varying the grain size from 0.1 to 1.0 mm. Results are shown in Fig. 7. Where the curve crosses zero is the point where the balance goes from offshore to onshore.

Fig. 7 shows that the direction of $\langle Q_{\text{infilt}} \rangle$ becomes more onshore with increasing grain size. This is in general accordance with nature, where coarser sediments are associated with beaches exhibiting steeper beachface gradients. The grain size at which the balance changes (the 'crossover' point, denoted here as d_{Q0}) is at about 0.55 mm, with a dominance of stabilisation–destabilisation below this value and a dominance of boundary layer effects above it. It can also be seen that around this area d_{Q0} is highly sensitive to errors or variations in the method of calculating Q_{infilt}. The other noteworthy point from Fig. 7 is that, below about $d = 0.25$ mm, the offshore influence of infiltration–exfiltration increases much more sharply with decreasing grain size, indi-

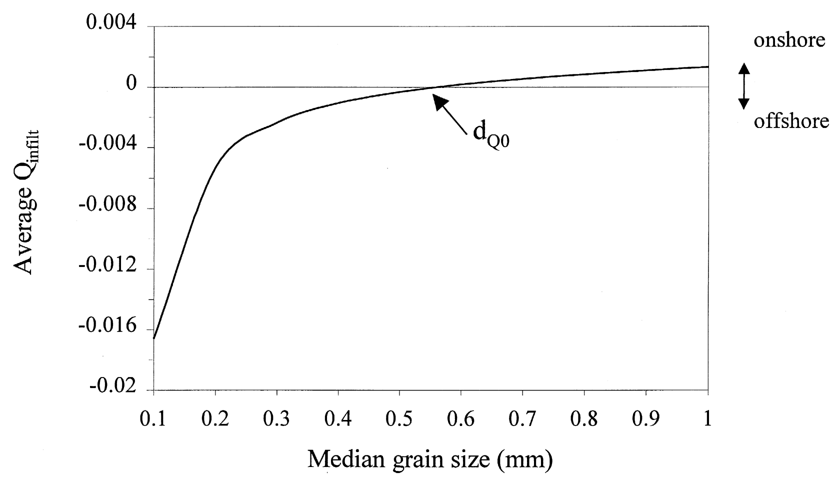

Fig. 7. Grain size dependency of the transport due to infiltration (Q_{infilt}), computed from Eq. (17) and averaged over the time-series. d_{Q0} is the point where $\langle Q_{\text{infilt}} \rangle$ goes from offshore to onshore.

cating that the dominance of stabilisation–destabilisation is much more pronounced at smaller grain sizes.

The other two parameters, which may be important, and which are not so straightforward to assess, are the friction factor (f) and the constant c in Eq. (14).

The estimation of a friction factor is always a difficult task, especially for flows in the swash-zone which could be considered either quasi-steady or oscillatory, and in which the depth varies considerably. Some methods demand iterative techniques, and estimates can vary over an order of magnitude. In TM98, f was kept constant at 0.01, after using a formula for oscillatory flow following Masselink and Hughes (1998). In the present study, it is considered more appropriate to use a formula for unidirectional flow, and the friction factor is not fixed but varies with water depth.

The constant c relates to the non-linear relation between shear stress and infiltration (Conley and Inman 1994). Its value seems to be dependent on whether or not the flow is considered oscillatory. In the present study, the uprush and backwash are considered as two separate quasi-steady flows, and in considering the value of c, TM98 have also assumed the flow to be quasi-steady. However, along with Masselink and Hughes (1998), they have assumed the flow to be oscillatory when choosing a formula for f.

It is therefore interesting to see how the balance between onshore and offshore transport might change if either f or c are varied. This was accomplished by calculating a family of curves of $\langle Q_{\text{infilt}} \rangle$ vs. d_{50} (similar to the one in Fig. 7) for a range of friction factors, and then calculating a further number of families of curves while allowing c to vary.

The result is a four-dimensional array which is difficult to visualise. Therefore, it was decided to extract the value of d_{Q0} from each $\langle Q_{\text{infilt}} \rangle$ vs. d_{50} curve, and plot this as a contour-plot in 'f–c space'. This then gives an idea of how variation of f and c affects the grain size at which the balance changes from offshore to onshore. Results are shown in Fig. 8. Each contour line has a unique $\langle Q_{\text{infilt}} \rangle$ vs. d_{50} curve associated with it, with its own d_{Q0} value. Note that for the purpose of this sensitivity test, the friction factor is forced to various different values, although in the present study f is dependent upon the depth, which changes with time.

It is instructive to focus on the region of Fig. 8 in the area around $d_{Q0} = 0.24$ mm, i.e. d_{50} for the

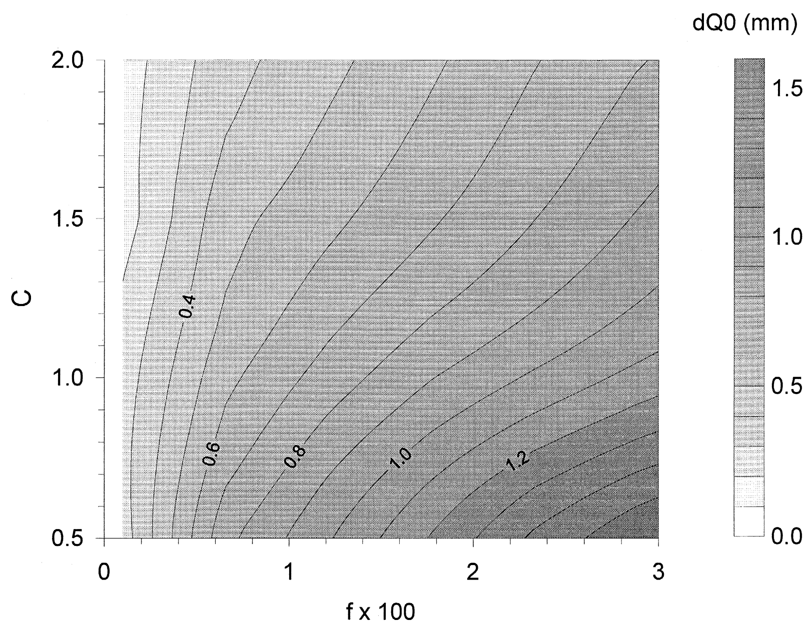

Fig. 8. Contours of the critical changeover value of grain size (d_{Q0}) for different values of friction factor and the constant c.

present study. If different methods were used in estimating f and/or c, resulting in a point in f–c space to the left-hand-side of the 0.24-mm contour (i.e. $d_{Q0} < d_{50}$), then the balance would change to onshore, indicating a dominance of boundary layer effects over stabilisation–destabilisation.

It can also be seen that, around this region, the calculations are much more sensitive to f than c. For the same values of f, using $c = 0.9$ (oscillatory flow) or $c = 2.0$ (steady flow) appears to make little difference. On the other hand, small changes in f may tip the balance one way or the other. If f had been assumed fixed in the present study, and the method of estimation had resulted in a value below about 0.006, then the balance probably would have been onshore. Therefore, careful consideration of the method of calculating the friction factor is important if correct assessment of the direction of influence of infiltration–exfiltration on the sediment transport is to be achieved.

Perhaps the most important aspect to consider is the changing relative magnitudes of the two processes of effective sediment weight and boundary layer modification as a function of beachface grain size. To examine this, two dimensionless parameters may be defined (c.f. TM98): τ_R is the shear stress with infiltration–exfiltration relative to without infiltration–exfiltration; W_R is the effective weight with infiltration–exfiltration relative to without infiltration–exfiltration. From Eq. (13):

$$\tau_R = \frac{\tau_w}{\tau_0} = \frac{\Phi}{e^{\Phi} - 1} \tag{27}$$

and from Eqs. (4) and (11):

$$W_R = \frac{W_w}{W_0} = \frac{s - 1 - 0.5w/K}{s - 1}$$

i.e.:

$$W_R = \frac{W_w}{W_0} = 1 - 0.5\frac{w}{K(s-1)}. \tag{28}$$

By calculating τ_R and W_R for a range of different grain sizes, while keeping all the other parameters constant, an idea may be obtained of whether, when the grain size is changed, either the shear stress changes more than the effective weight or vice-versa.

To evaluate Eqs. (27) and (28) over a range of grain sizes, values of $|u|$ and w of 0.1 and 0.004 m s^{-1} (Turner and Nielsen, 1997) have been used. Note that, in this case, since w has been chosen as positive upwards (exfiltration), then through-bed flow will result in a simultaneous reduction of both shear stress and effective weight. Fig. 9 shows a plot of W_R and τ_R against d_{50}. It can be seen that, at small

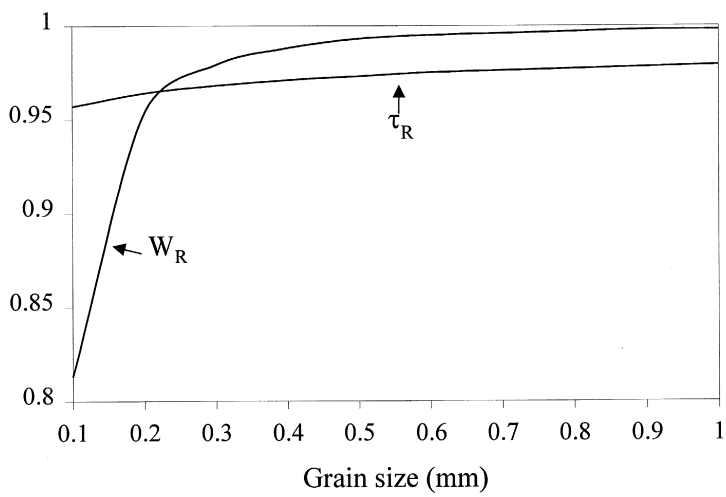

Fig. 9. Sensitivity to grain size of relative shear stress (τ_R) and relative effective weight (W_R).

Table 2
Comparison of relative weight (W_R) and relative shear stress (τ_R) dependence on grain size, at different ranges of grain sizes

d (mm)	W_R slope	τ_R slope	Ratio
$0.1 < d < 0.3$	0.831	0.055	15.1
$0.3 < d < 1.0$	0.023	0.015	1.53

grain sizes, W_R decreases rapidly with decreasing grain size, whereas the slope of τ_R remains fairly constant with grain size. This suggests that stabilisation–destabilisation has the greater influence on the characteristics of the $\langle Q_{infilt} \rangle$ vs. d_{50} plot (Fig. 7).

To summarise the difference in sensitivity of the two processes to changes in grain size, the curves in Fig. 9 were split into two sections (0.1 mm $< d_{50} <$ 0.3 mm and 0.3 mm $< d_{50} <$ 1.0 mm) and each section was linearly regressed. The ratio of the slopes of the regression lines were then found for each section of the curves (see Table 2). Above $d_{50} = 0.3$ mm, effective weight has about 50% more sensitivity than shear stress to changes in grain size, and below $d_{50} = 0.3$ mm, effective weight is 15 times more sensitive than shear stress to changes in grain size. That is to say, if the grain size changes, then this will affect the stabilisation–destabilisation of the sediment more than it will affect the boundary layer modification.

In summary, if two different beaches are considered, then the difference in grain size will change the way infiltration–exfiltration biases the sediment transport, primarily through the effective weight of the sediment. The grain size does not need to be very different for infiltration–exfiltration to bias the sediment transport onshore on one beach, but offshore on another. Inspection of Fig. 8 reveals that if a fixed friction factor of 0.01 was used as in TM98, then the critical changeover point (d_{Q0}) would be 0.45 mm. The grain size in TM98 was larger than this, confirming their findings of onshore transport dominance. The grain size in the present study was smaller than d_{Q0}, suggesting offshore dominance.

8. Discussion

The principle finding from the present study is that there appears to be some critical grain size below which effective weight effects dominate, causing infiltration–exfiltration to bias the transport offshore, and above which modified boundary layer effects dominate, causing infiltration–exfiltration to bias the transport onshore. The apparent conflict between the present study and that of TM98 is therefore explained by the fact that TM98 was undertaken on a significantly coarser beach.

Obtaining a value for the critical changeover point (d_{Q0}) is not straightforward, and it is sensitive to the method used when estimating various empirical constants, especially the friction factor. The value of d_{Q0} appears to lie somewhere between 0.45 mm (using the methods of TM98) and 0.58 mm (suggested by Nielsen, 1998). Other differences in approach may also be important, such as modelled (TM98) vs. measured (present study) velocities, and linear (Nielsen, 1998) vs. non-linear (present study and TM98) velocity–stress relationships.

It is clear that if further studies are to be conducted to obtain a value for the critical changeover point, then methods must be standardised. Different experimental approaches and methods of estimating the various constants can make the results appear contradictory. The friction factor seems to be particularly important, and also one of the most difficult parameters to estimate.

A comprehensive analysis of friction factors for the uprush was performed by Hughes (1995), and it was suggested that the flow should be considered sheet flow (Wilson, 1988). The most appropriate formulation would therefore be:

$$f = 20 \ln\left(0.5\frac{h}{\theta d}\right)^{-2}. \qquad (29)$$

Since the Shields parameter (θ) appears in this formula, which is in turn dependent on the friction factor, then iterative techniques would have to be used to solve it. Also, the work of Hughes (1995) was based upon a model of uprush following bore collapse on a steep beach, which is quite different from the conditions encountered in the present study.

As mentioned above, TM98 assume oscillatory flow when calculating f, but steady-flow when choosing a value for c. In the present study, quasi-steady flow is assumed for both. Oscillatory friction factor formulae (albeit different ones) were also used by Hughes et al. (1998) and Masselink and Hughes (1998), who acknowledge that Eq. (29) (above) might be more appropriate. Even if an oscillatory formula was used, it would be far from obvious which one to choose for the swash-zone (see Nielsen, 1992). Obviously, more work, perhaps in the laboratory, is required to find out the nature of the boundary layer in the swash-zone, and the most appropriate way to estimate the friction factor.

For the present study, the relative effect of infiltration–exfiltration over a single swash cycle was estimated to be a reduction of about 10% of the total sediment moved on the uprush and an increase of about 4.5% of the total sediment moved on the backwash. Although the direction is different from that in TM98 (due to grain size), infiltration–exfiltration has more influence on the uprush than on the backwash in both studies. Inspection of the $-\partial h/\partial z$ time-series shows that the uprush is characterised by higher, more abrupt downward forces brought about by the sudden arrival of the swash-front at the measurement position, whereas the backwash is characterised by longer duration but lower magnitude upward forces. The difference in the nature of uprush and backwash flows is therefore further highlighted.

The magnitudes of infiltration–exfiltration influence on the uprush and on the backwash were estimated by TM98 by comparing simulated peak transport rates. If this is done for the single swash cycle analysed here, an approximate 16% decrease in peak uprush transport and a 6% increase in backwash transport is found. TM98 obtained uprush increases of between 10% and backwash decreases of 5% to 10%, for a position in the mid-swash-zone. They also suggested that the influence of infiltration–exfiltration decreases with increasing distance up the beach-face.

Baird et al. (1996) performed model simulations using the field data of Hughes (1992) to investigate the hypothesis that fluidisation of the bed might occur within the swash zone during the backwash. They concluded that, for one case out of five, fluidisation might be likely on the very last stages of the backwash. This was achieved by adjusting the assumed value of K to 0.0002 m s^{-1}, about five times smaller than that obtained in the present study.

The estimation of K is, again, not straightforward and various empirical formulations are normally used, based on the grain size, porosity and sorting characteristics. In the present study, the formula of Bear (1972) was used, which is the most up to date

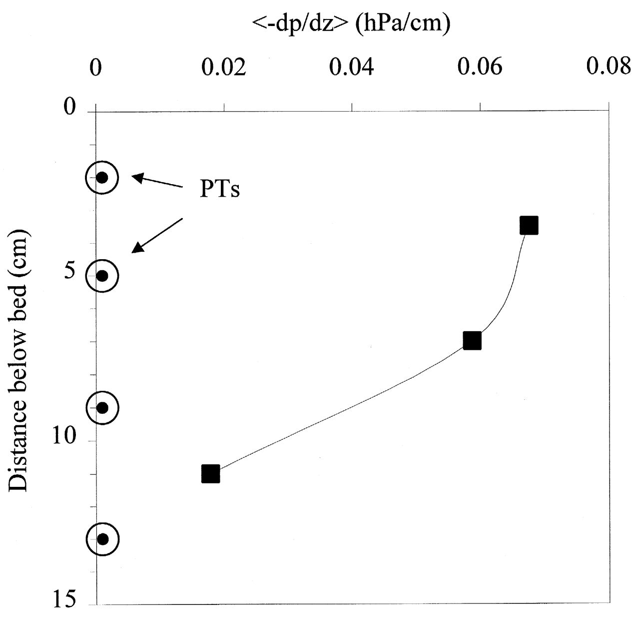

Fig. 10. Schematic illustration of the vertical position of the pressure transducers below the bed, and the individual pressure gradients, averaged over the time-series, between each pair of sensors.

formula suggested by Domenico and Schwartz (1998). Baird et al. (1998) found that, by using the older method of Krumbein and Monk (1942), values were an order of magnitude smaller than those carefully measured with permeameters. For the grain characteristics at Canford Cliffs, UK (the field site used by Baird et al., 1998), estimation of K using the formula of Bear (1972) results in a value much nearer to that measured.

Therefore, it appears that fluidisation is of lesser importance, and no field evidence is available (including from the present study) to suggest that fluidisation occurs in the swash-zone. The fact is also highlighted that care must be taken in any estimation of K, which is, along with the friction factor, another parameter notoriously difficult to estimate.

Since the pressure was originally measured at four depths within the bed, it was considered instructive to note how the pressure gradient might change with depth. Fig. 10 shows a schematic representation of the position of each sensor and the time-averaged pressure gradient between each pair of sensors $\langle -\partial p/\partial z \rangle$. The diagram shows that the gradients decrease with distance below the surface, suggesting that pressure propagation attenuates with depth. In the present study, to allow comparison with the results from previous work, the pressure gradient between the top and bottom sensors were used as these were positioned at depths closely corresponding with those of Turner and Nielsen (1997) and TM98. It is important to stress that using pressure gradients at different depths from those previously published would only have added to the uncertainty, with the already highlighted difficulty estimating parameters such as K and f. (K, for example, can vary over an order of magnitude depending on the method used to estimate it.) The implications of the attenuation of pressure with depth for sediment transport should be the topic of future investigation.

9. Conclusions

- Examination of time-series of sub-surface pore pressures has shown that upwards-directed pressure gradients on the backwash are not sufficient to cause fluidisation of the top layer of sediment leading to enhanced offshore transport.
- A review of the theory has been presented concerning the two competing processes which may be important in altering the uprush and backwash transport through infiltration–exfiltration, namely (a) stabilisation or destabilisation of the surface layers, and (b) boundary layer thickening or thinning. A modified Shields parameter has been derived with extra terms to take account of these processes, following the work of Nielsen (1998) and Turner and Masselink (1998).
- It was found that the net direction of Q_{infilt} was offshore for the data in the present study, i.e. uprush transport was inhibited and backwash transport enhanced by infiltration–exfiltration.
- By allowing the grain size to vary in the computations, it was found that, above a particular critical grain size, the effects of infiltration–exfiltration change from biasing the transport offshore to onshore, indicating a shift from a dominance of stabilisation–destabilisation to a dominance of boundary layer effects.
- The exact value of the critical grain size changeover point (d_{Q0}) is not straightforward to estimate, and it has been suggested that experimental methods and the method of estimating various constants be standardised before a reliable value of d_{Q0} can be found.
- Sensitivity tests on the friction factor (f) and the constant (c) in the shear-stress–velocity relationship have found that, although c is less sensitive, relatively small changes in the estimation of f might change the direction of the apparent influence of infiltration–exfiltration. A suitable formula for f in the swash-zone has not yet been found.
- The net influence of infiltration–exfiltration over a single swash cycle was to decrease the total sediment transported by about 10.5% on the uprush, and to increase the total sediment transported by about 4.5% on the backwash.

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