SEEPAGE EFFECTS ON SEDIMENT TRANSPORT BY WAVES AND CURRENTS.

T. E. Baldock [1] and P. Holmes [2]

Abstract

This paper considers the influence of seepage on the motion and transport of sediment. Under wave motion, steady upwards seepage (injection) increased erosion, while downwards seepage (suction) stabilised the bed. Conversely, seepage in the presence of a steady flow produced negligible changes in the sediment motion. A theoretical analysis examines the stability of the sediment particles and sediment bed under these conditions and provides an explanation for the different seepage effects. Seepage across the sediment/fluid interface also had a strong influence on the growth of sand ripples, even at pressure gradients of order 0.1. These results suggest that ripple dynamics in the nearshore may be affected by the watertable level and drainage within a beach.

1) Introduction

The stability of sediment particles under the influence of pressure gradients within the sediment bed is considered to be important with respect to the type and rate of sediment transport under both steady and oscillatory flows (Nielsen, 1992) However, previous work has provided conflicting results (Martin, 1970; Willets and Drossos, 1975; Oldenziel and Brink, 1974;Rao et al., 1994) and the effects of pressure gradients on sediment dynamics are not immediately obvious (Oh and Dean, 1994).

The rate and nature of sediment transport under steady flows and wave induced motions is generally considered to be dependent on the forces on the individual sediment particles. These include gravity forces, the surface drag force, pressure forces due to pressure gradients within the fluid, a lift force due to flow over the sediment particle and a seepage force due to flow across the fluid/sediment interface (Sleath, 1984). It may also be necessary to consider the stability of the sediment bed as a whole. In this instance the

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effective stresses within the sediment may be increased, reduced or vanish completely (fluidisation) due to pressure gradients within the sediment. However, the effects of these pressure gradients on sediment transport are unclear and previous work has provided conflicting results. For example, in steady flows, Martin (1970), Watters and Rao (1971) and Willets and Drossos (1975) found that seepage did not affect sediment motion, while Oldenziel and Brink (1974) found the opposite to be true. The only experimental evidence under oscillatory flow in a water tunnel appears to be that from Kruijt (1976), who again found no significant effects. These results all pertain to steady vertical seepage, and as far as the authors are aware, no study has been carried out under oscillatory wave motion.

Surface gravity waves and bores will induce both vertical and horizontal transient pressure gradients within a sediment bed. The vertical pressure gradients induce flow into the bed under wave crests (suction) and upwards out of the bed under the wave troughs (injection). However, as noted by Packwood and Peregrine (1983), the vertical wave induced pressure gradients are approximately linearly proportional to the bed thickness. Consequently, scale modelling of sediment motion may be influenced by the relatively thin beds generally used in laboratory studies. Indeed, evidence to this effect was found by Conley and Inman (1992), who suggested that differences in bed ventilation might be responsible. Madsen (1974) showed experimentally that horizontal pressure gradients could be sufficient to fluidise a sediment bed under breaking waves while Yamamoto (1978) suggested that large steep waves and tsunamis transport huge amounts of sediment because the bed is fluidised by horizontal pressure gradients.

Previous work has also suggested that the pressure gradients and the seepage flow induced within beaches may be an important factor governing both long term beach morphology and short term (storm duration) beach evolution (Oh and Dean, 1994; Turner, 1995). In these instances, an unsaturated beach face appears to promote steepening of the profile, while a saturated beach face tends to result in a flattening of the beach profile. However, the mechanism by which the watertable influences the beach dynamics is not obvious. For example, Oh and Dean (1994) found that a raised water table increased shoreward transport, contrary to most previous studies (e.g. Emery and Foster, 1948; Waddell, 1976), while a lower water table appeared to result in increased stability and little profile change. Numerical calculations also suggested that the pressure gradients induced by the change in watertable were too small to influence the stability of the sediment.

2) Theory

The pressure distribution within sediments was first considered by Putnam (1949) and later expanded upon by Sleath (1970) and others. Sleath's (1970) solution was based on the assumption of an incompressible fluid, grain particles and grain skeleton. Flow velocities were then derived assuming Darcy's law for flow in a porous medium. A number of more exact solutions include the effects of fluid compressibility and the deformation of the grain skeleton (e.g. Yamamoto et al, 1978; Madsen, 1978). Darcy's law gives flow velocities in a porous medium as:

$$u=-ki_x, \quad v=-ki_y \qquad (1)$$

An explanation for this anomaly may be found by comparing the fall velocity of the sediment particles with the velocity of the flow across the fluid/sediment interface. If Darcy flow applies, then the flow rate across the interface is given by equation (1). Prior to piping, the maximum possible flow velocity, V_s, out of a sand bed will therefore be approximately equal to the bed permeability, k, and of the order 0.25k for lightweight anthracite beds. This flow velocity is generally much smaller than the fall velocity of the sediment, w. For example, for a sand with $d_{50} \approx 0.2$mm, the permeability will be of order 10^{-4}m/s but the fall velocity is of order 10^{-2}m/s (van Rijn, 1989).

This difference of two orders of magnitude remains much the same for coarser sand. Consequently, once a sediment particle lifts out of its bed recess and the seepage force no longer acts, the fall velocity of the particle, w, will dominate over the vertical flow velocity V_s (figure 1). The effect of vertical seepage on a sediment particle rolling over the surface of the bed will therefore be minimal. The same argument applies in reverse in the case of downwards seepage and the fall velocity of the sediment particle again dominates the process. Note that the effect of boundary layer changes due to the seepage flow are not considered separately in this study. Consequently, the experimental results include both the effects of seepage and boundary layer changes together. Therefore, extrapolating the results from these flow conditions to radically different flow conditions or sediment sizes should be viewed with caution.

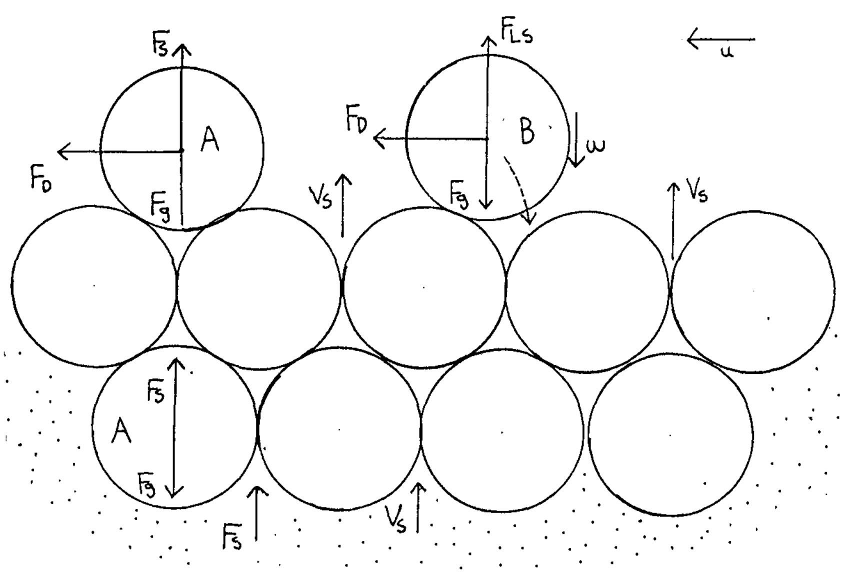

Figure 1. Forces and fluid velocities acting on particles on and just above a sediment bed at incipient fluidisation:
F_g - gravity force, F_s - seepage force, F_d - drag force, F_{LS} - lift force due to seepage velocity, u - free stream velocity, w - particle fall velocity, V_s - seepage velocity.
A: F_s=F_g, B: F_g>>F_{LS}, w>>V_s.

3) Experimental Method And Instrumentation.

The experiments were conducted in a 12m long combined wave-current flume in the Civil Engineering Department at Imperial College (figure 2). Waves can be absorbed at any position within the flume by a block of polyether foam and the reflection coefficient under these conditions was found to be less than 10%. In order to allow the thickness of the sediment bed to be varied whilst maintaining the same flow conditions in the flume, a raised bed was additionally installed. Vertical seepage was induced by means of a seepage box installed within the sediment bed, allowing a seepage flow over a length of 1m across the full width of the flume. The seepage box comprised a lower section 50mm deep, overlain by a baffle plate and 30mm of polyether foam. The foam was then covered with fine wire gauze to prevent the ingress of sediment. The seepage flow was induced through a pipe running under the raised bed. Upwards seepage was controlled through a tap and valve connected to a large constant head tank, while downwards seepage was induced by siphoning to a sump, the discharge in either case being proportional to the head across the sediment bed. During this phase of the investigation the depth of sediment above the box was kept constant at 70mm. For convenience, the origin of the horizontal co-ordinate in all figures is taken at the upstream end of the box.

Both the dynamic and steady pressure gradients were measured by a technique developed by Baldock and Holmes (1996). This uses probes connected to pressure transducers via semi-rigid flexible tubing to determine the pressure at any location quickly and easily, with minimal disturbance of either the fluid or sediment bed. When determining steady pressure gradients, the probe system requires no calibration and errors in the measurements are of order 5%. Baldock and Holmes (1996) also show the dynamic response of the probe system is good when measuring transient pressure gradients, with errors of order 10%-15%.

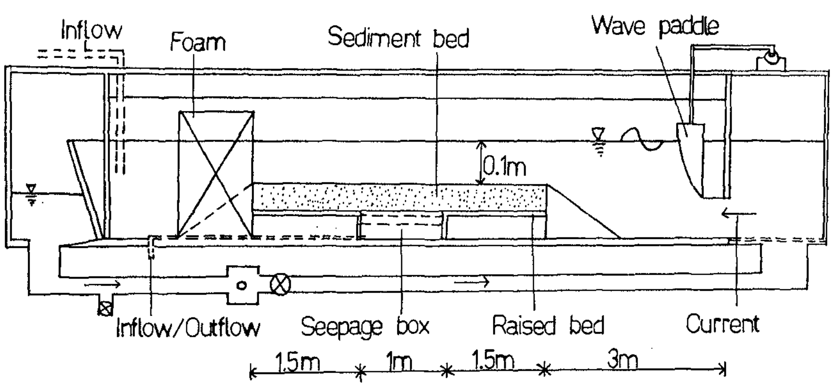

Figure 2. Wave and current flume.

where k is the coefficient of permeability, i_x and i_y are the dimensionless pressure gradients in the horizontal and vertical directions respectively, and u and v the corresponding flow velocities. Note that flow into the bed (suction) corresponds to a positive vertical pressure gradient. Fluidisation, or liquefaction, of the sediment bed occurs when the pressure gradient reduces the effective stress within the sediment to zero (e.g. Smith, 1968). For vertical seepage this occurs when the vertical pressure gradient exceeds the critical value i_{cy} given by:

$$i_{cy} = -(s-1)(1-n) \tag{2}$$

where s is the specific gravity of the sediment and n is the porosity, typically of order 0.4-0.6. For sand, this critical value is generally found to be approximately equal to 1, while for anthracite (s=1.4), the critical value is of order 0.2. The critical horizontal pressure gradient, i_{cx}, required for bed fluidisation is smaller than that needed with vertical seepage (Madsen, 1974):

$$i_{cx} = (s-1)(1-n)\ \tan\phi \tag{3}$$

where ϕ is the internal angle of friction. For typical values of ϕ of 35°, the critical horizontal pressure gradient is of order 0.5-0.6 for natural sand and 0.14 for anthracite. If both a vertical and horizontal pressure gradient act simultaneously, then failure of the bed material will occur earlier. In this instance the horizontal pressure gradient required for fluidisation of the bed will reduce to:

$$i_{cx} = (s-1)(1-n)\ \tan\phi\ (1 - i_y/i_{cy}) \tag{4}$$

Hence, if a steady and critical vertical pressure exists (i_y=i_{yc}), then the sediment bed will be unable to resist any additional horizontal pressure gradients. Therefore, even the smallest degree of wave motion or turbulence will shear the sediment layers within the bed. If, however, the free fluid flow is steady (i.e. a current), there will be no significant additional horizontal pressure gradient and no horizontal shearing within the bed.

The stability of the interfacial particles is generally considered to be dominated by the drag force and is expressed in terms of the Shields parameter, θ. Considering flow conditions where the sediment bed is on the point of incipient fluidisation, then the particles within the bed are completely supported by the upwards seepage, although the interfacial particles might experience a smaller seepage force (e.g. Martin 1970). A modified Shields parameter could therefore be written in the form:

$$\theta' = \frac{\theta}{(1 - i_y/i_{yc})} \tag{5}$$

As a result, the Shields parameter becomes large as the bed approaches fluidisation and we might expect the interfacial particles to become highly unstable. Indeed, Loveless (1994) suggests that the particles will be ejected into the flow. Incipient sediment motion should therefore occur at very much smaller flow velocities than normal, contrary to most of the previous experimental work discussed above

A series of preliminary measurements were made in order to determine the properties of the sediment bed and the flume set-up. The sediment bed was laid underwater and then repeatedly stirred in order to exclude as much air as possible, subsequently remaining submerged for the duration of each test. The bed permeability was measured in-situ at a number of locations with a falling head permeability test. The porosity of the bed material was also measured under conditions that approximated those within the flume. Sand ripple growth was promoted by introducing artificial disturbances. Ripple growth rates could therefore be measured under different seepage conditions. Both sand and lightweight anthracite particles were used in this study, the latter chosen to highlight seepage effects and aid visual and video observations. Table 1 shows the relevant sediment properties. Finally, as a check on the pressure measurement system and the method of laying the sediment bed, the pressures within a sand and anthracite bed were compared to the solution presented by Sleath (1970), with good agreement (figure 3).

Sediment	Specific gravity, s	d_{50} (mm)	Permeability, k (m/s)	Porosity, n
Sand	2.65	0.2	2×10^{-4}	0.6
Anthracite	1.4	3	$1\text{x}10^{-2}$	0.5

Table 1. Sediment properties.

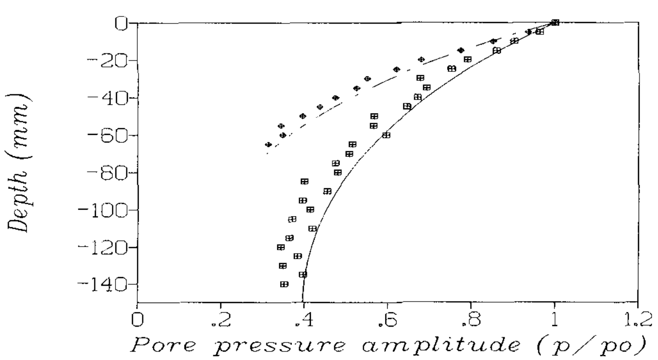

Figure 3. Pore pressure amplitude within a sediment bed under progressive waves. ■■■ Sand, T=0.7s, ——— Sleath (1970), ♦♦♦ anthracite, T=0.5s, — — Sleath (1970).

4) Experimental Results

Bed thickness

The influence of wave induced vertical pressure gradients was examined by comparing the conditions required for incipient motion of lightweight anthracite particles over a thin (10mm) and thick (150mm) sediment bed. Three different wave periods were selected and the tests were carried out by slowly increasing the wave height until incipient motion commenced. At incipient motion, the measured vertical pressure gradients, i_y, just below the surface of the thick bed were about 0.08, approximately half those required for complete fluidisation of the anthracite, and negligible for the thin bed. Careful observation suggested that incipient motion of the anthracite particles commenced at the same wave height ($\theta \approx 0.06$), regardless of the bed thickness. Vertical wave induced pressure gradients therefore appear to have no significant effect on incipient sediment motion, and are also unlikely to effect sediment transport rates, at least prior to sheet flow conditions. This is consistent with the discussion in section 2, since at the time of maximum and minimum bed-stability wave induced horizontal pressure gradients are zero.

The effects of a steady vertical seepage across the fluid/sediment interface were examined under conditions of both suction and injection using the seepage box arrangement (figure 2). For the fine sand, a vertical pressure gradient, i_y, of 0.6 was used in both instances. The effective stress within the bed was therefore reduced to close to zero during injection and nearly doubled under suction. The vertical pressure gradients were reduced to 0.2 for the anthracite bed, approximating the same effective stress conditions within the bed. In each case the experimental conditions remained identical except for the seepage across the sediment/fluid interface.

With a steady seepage across the sediment bed, a current was introduced within the flume and then slowly increased until the threshold of sediment motion was reached. For both the sand and anthracite beds, incipient sediment motion started at Shields numbers of about 0.045, irrespective of the seepage direction. These results are again in agreement with the argument set out in section 2 and consistent with a number of previous studies (e.g. Martin, 1970; Willets and Drossos 1975; Kruijt 1976). However, in order to examine the effects of the seepage flow in more detail, a closer examination of the bed material during piping was carried out using the larger anthracite particles.

Initially, in the absence of a current, the seepage flow was slowly increased until piping first occurred over a small region of the bed. Under these conditions, sediment particles were not ejected into the body of the fluid but appeared very unstable within their bed recesses. In fact, close inspection suggested that the particles within the piped area appeared to vibrate. This is entirely consistent with transient nature of the seepage force as particles start to lift out of their bed recesses and then re-settle under their own weight. Furthermore, on the re-introduction of the steady current, incipient motion of the particles within the piped area occurred at the same flow velocity as previously and at the same time as incipient motion commenced at adjacent areas of the bed that were not piped. This therefore shows that as soon as a particle moves out of its bed recess, the gravity force completely dominates the lift force due to the small seepage velocity out of the bed. Consequently, steady seepage has very little effect on the stability of the interfacial particles.

Wave motion

Under wave motion, the sediment bed is subject to both vertical and horizontal pressure gradients, the latter being independent of the bed thickness. The effects of an additional steady seepage on the net sediment transport rate were now examined, initially using anthracite particles. Waves with a height of 38mm and wave period of 1s were selected for use in these and all subsequent tests, corresponding to a Shields number of about 0.12 and giving maximum measured horizontal pressure gradients, i_x, of 0.14, very close to the conditions required for local fluidisation of the bed. Net sediment transport rates were inferred from bed level changes.

Figure 4a compares the bed level changes found without seepage with those obtained during injection. With no seepage, the net sediment transport was positive due to the shallow water wave conditions but tended to accumulate at the anti-nodes of the weak standing wave system within the flume, i.e. where the wave induced horizontal velocity was a minimum. The results obtained during injection show a significant change, with erosion occurring over the weakest area of the bed (0<x<50cm) and further upstream. The steady vertical seepage was found to have an effect at pressure gradients, i_y, as low as 0.05 and the net positive sediment transport rate increased fourfold when the bed was on the point of fluidisation (i_y=-0.2, figure 4c).

Close inspection of the bed using video analysis showed that the seepage had a clear effect on the sediment transport mechanism. The sediment within the bed tended to lift during the passage of a wave trough and the upper layers of the bed were then sheared by the horizontal pressure gradient and positive horizontal velocity induced by the approaching wave crest. Sediment was therefore transported in the direction of wave motion. The flow into the bed under the crest subsequently reduced the effect of the upwards seepage, stabilising the bed. However, although the wave induced horizontal pressure gradients were symmetric about the wave crest, a similar mechanism was not observed following the passage of a wave crest. This appears to confirm the results of Takahashi et al (1994), who suggested that the phase difference between the bed motion and wave motion is less than 180°.

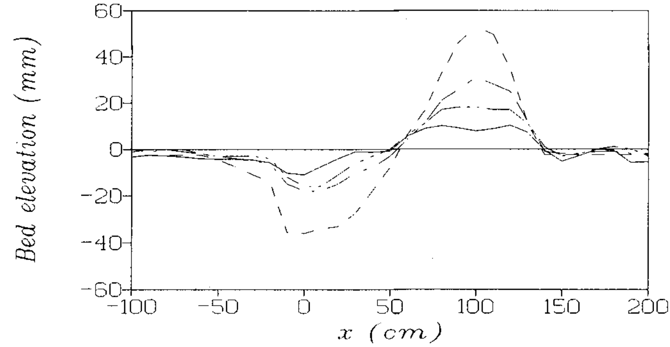

Figure 4a. Evolution of an anthracite bed under wave motion with steady vertical seepage (injection).
———— i_y=0, — — — i_y=-0.2, —— — —— i_y=-0.1, ———— — — ———— i_y=-0.05.

The behaviour of the sediment within a locally piped region was again closely observed. This also showed that even under wave motion the interfacial particles were largely unaffected by the seepage flow, with no relative movement between these particles and those within the bed. However, the sediment bed within the piped area behaved largely as a fluid, oscillating to a considerable depth under the smallest wave induced pressure gradients. Note that the piped bed had zero effective strength and, consequently, was unable to sustain a slope, leading to negligible net sediment transport.

The experiment was then repeated with suction applied across the fluid/sediment interface. In this instance the steady pressure gradients were in the range i_y=0-0.15, approximately doubling the effective strength of the bed. Suction was found to increase the stability of the sediment bed and consequently the shearing of the upper layers of the bed was prevented. The net positive sediment transport rate was therefore reduced (figures 4b&c). It is, however, very important to note that this reduction in the transport rate was not a result of an increase in the stability of the interfacial particles. The transport rate of these particles did not appear significantly affected by the applied suction, even when i_y=0.15. This is consistent with the data obtained previously under steady flows. In these instances the reduction in the transport rate compared to the case without seepage predominantly arose due to the reduced shearing of the upper layers of the sediment bed.

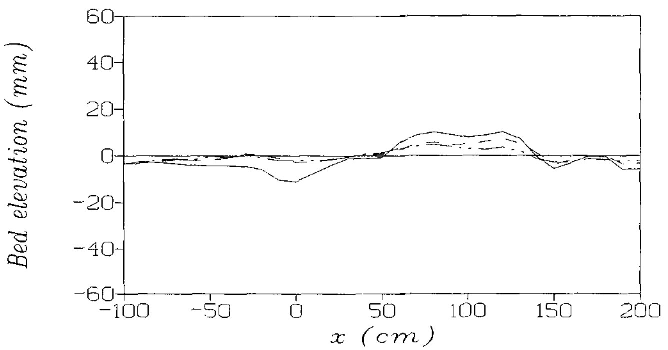

Figure 4b. Evolution of an anthracite bed under wave motion with steady vertical seepage (suction). ———— i_y=0, — — — i_y=0.1, —— — —— i_y=0.15.

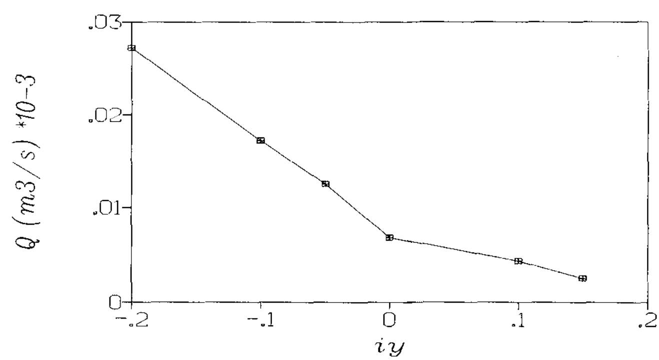

Figure 4c. Variations in the net positive sediment transport rate for anthracite under wave motion with steady vertical seepage.

Sand ripple dynamics

Seepage across the fluid/sediment interface was also found to have a significant effect on the formation and growth of sand ripples. For example, figure 5 shows the evolution of a fine sand bed after five hours of wave action. With no seepage, bed level changes occurred due to the gradual formation of ripples, leading to suspended sediment transport and eventually the generation of larger scale features. Little change was observed when repeating the experiment with an upwards seepage flow (injection); however a considerable difference arose when suction was applied. In this instance, the sand bed over the seepage area (0<x<100cm) remained plane during five hours of wave action, with no ripple formation occurring, despite ripple formation either side of this region. It has been drawn to the authors' attention that Sakai and Gotoh (1996) found that the bed configuration and ripple regime could be changed by an oscillating pressure gradient across the bed.

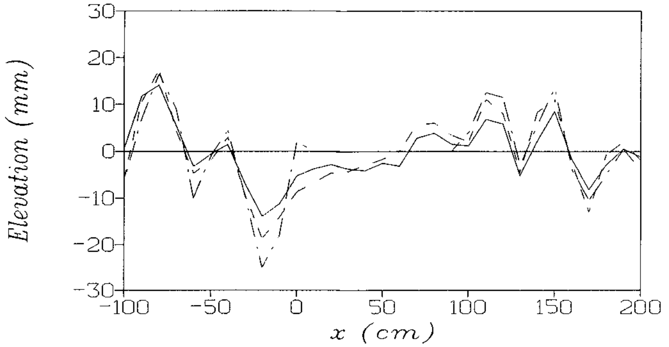

Figure 5. Evolution of sand bed after five hours of wave motion with steady seepage. ——— i_y=0, — — — i_y=-0.6 (injection), —— — —— i_y=0.6 (suction).

The growth rate of sand ripples on the fine sand bed with additional suction and injection was therefore compared to that over an adjacent region of the bed without seepage. Two discontinuities were introduced to promote ripple growth at specific positions on the bed. The first was at x=50cm, in the centre of the seepage area. The second, which acted as a control, was positioned at x=150cm, downstream from the seepage area.

Each discontinuity consisted of a hollow approximately 5mm wide and 1-2mm deep across the full width of the flume, formed by pushing a perspex wedge a fixed distance into the bed. After the onset of fluid motion, ripples started to grow from these discontinuities, spreading in both directions under wave motion and downstream in the presence of a steady current. The ripples could initially be classified as rolling grain ripples but subsequently grew to form vortex ripples. The effect of the seepage was then investigated by comparing the ripple growth rates at the two positions (the ripple growth rate at the two positions was the same when there was no seepage flow).

During injection, the upwards seepage started to have a significant effect at pressure gradients, i_y, as low as -0.2, with the ripple growth rate increasing nearly threefold as the bed approached conditions of local piping, i_y=-0.6, figure 6a. Close inspection of the bed showed that the ripple growth rate increased due to the increased instability of the bed surface as a whole, with small ridges of sediment forming across the flume. Indeed, at very high pressure gradients, the bed tended to ripple spontaneously all over the seepage area and not just at the position of the initial discontinuity. This is consistent with the analysis outlined in section 2 and was due to the local shearing of the surface layers of the sediment bed by the additional wave induced pressure gradients. This shearing of the bed caused small distortions in the bed surface, prompting the formation of sand ripples.

In contrast, suction prevented the formation of ripples and took effect at steady pressure gradients as low as i_y=0.05 (figure 6b). Furthermore, at gradients in excess of 0.1, ripples did not grow at all, which confirmed the results obtained previously (figure 5). It is, however, important to note that the suction did not prevent the motion of the interfacial particles, the motion of which was similar at both the control section and over the seepage area. Seepage effects on ripple formation under steady flows appeared minimal, again due to the lack of additional wave induced pressure gradients and hence minimal shearing and deformation of the bed surface (figures 7a&b)..

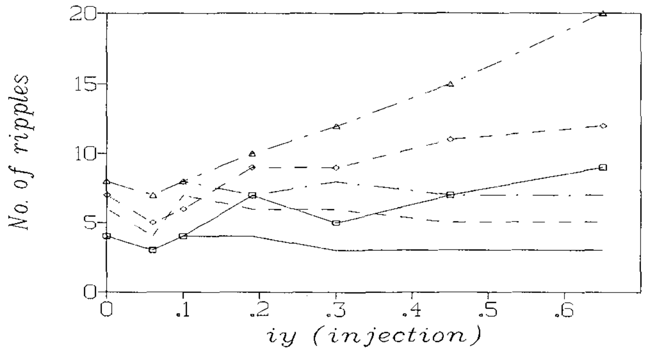

Figure 6a. Ripple growth rates under wave motion during injection.
——— control (t=5mins), ——■—— t=5mins, — — — control (t=10mins), — ▾ — t=10mins, —— — —— control (t=15mins), —— —▴— —— t=15mins.

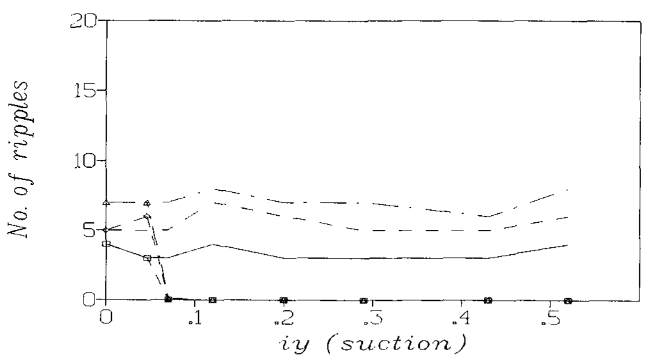

Figure 6b. Ripple growth rates under wave motion during suction.
——— control (t=5mins), ——■—— t=5mins, — — — control (t=10mins), — ▾ — t=10mins, —— — —— control (t=15mins), —— —▴— —— t=15mins.

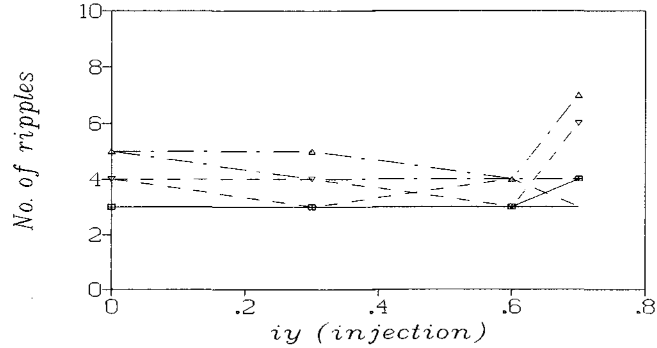

Figure 7a. Ripple growth rates under steady flow during injection.
———— control (t=5mins), ——■—— t=5mins, — — — control (t=10mins),
— ▾ — t=10mins, ——— — ——— control (t=15mins), ——— —▴— ——— t=15mins.

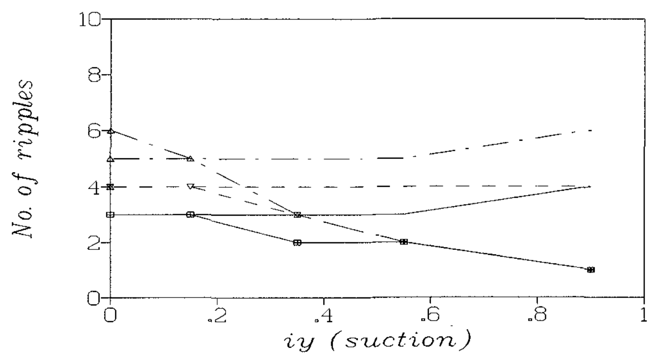

Figure 7b. Ripple growth rates under steady flow during suction.
———— control (t=5mins), ——■—— t=5mins, — — — control (t=10mins),
— ▾ — t=10mins, ——— — ——— control (t=15mins), ——— —▴— ——— t=15mins.

The effect of suction on existing ripples (relic bedforms) was also examined. If the ripples were initially very small (i.e. rolling grain ripples) then they were slowly washed out by the wave motion and the bed tended to return to the initial plane state. If, however, the ratio of the ripple height to wavelength exceeded a value of about 0.1, then the ripples were not washed out, but neither did they continue to grow. These effects will, however, be dependent on the relative magnitude of the applied suction, the sediment grain size and the wave induced orbital velocity. Nevertheless, the results suggest that both the watertable level and/or the presence of a beach drain could influence the formation and growth of ripples within the nearshore region. This might then affect the quantity of both the bed load transport and the amount of sediment put into suspension.

6) Conclusions

On a plane sediment bed, vertical wave induced pressure gradients, i_y, were found to have no direct effect on the conditions required for incipient sediment motion. Steady vertical seepage across the sediment/fluid interface was also found to have no discernible effect on the threshold of motion of the sediment particles in the presence of a current, even when the sediment bed was locally fluidised. In contrast, steady vertical seepage in combination with wave motion had a significant effect on net sediment transport rates. Injection was found to promote erosion of the sediment, through shearing of the upper layers of the weakened bed by the additional wave induced horizontal pressure gradients. Conversely, suction stabilised the bed material, reducing wave induced shearing and reducing the net transport rate.

At low Shields numbers, seepage flow across the sediment/fluid interface appears to have very little effect on the threshold of motion or sediment transport rates. This is because the seepage force no longer acts on sediment particles rolling or saltating over the bed. Consequently, the vertical forces on moving sediment particles are little changed in the presence of a seepage flow. However, although sheet flow conditions could not be modelled in this study, the results do suggest that injection will enhance sediment transport by sheet flow, while suction will tend to reduce the occurrence of sheet flow conditions (neglecting boundary layer changes). In this instance, the sheet flow layer may act as a fluid/sediment matrix, within which a seepage force can exist. Seepage will therefore alter the effective weight of the sheet flow layer, enhancing or reducing mobility. In practical circumstances, such as in the swash zone, the experimental results therefore appear consistent with the suggestion that the sediment transport rate will differ over saturated and unsaturated beach faces. Further work is therefore required to identify if a modified Shields parameter will describe sediment transport rates under these conditions.

Vertical seepage greatly influenced the formation and growth rate of ripples on a sand bed at pressure gradients typically induced within beaches due to changes in watertable levels, infiltration/exfiltration and beach drainage. Therefore, since both bed load and suspended load sediment transport are influenced by the ripple regime, the effects of seepage on ripple dynamics may have important implications for net sediment transport rates in the nearshore. This, however, requires further work and should isolate the effects of turbulence and boundary layer changes (e.g. Turcotte, 1960).

Acknowledgements

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