FIELD MEASUREMENTS OF SWASH INDUCED PRESSURES WITHIN A SANDY BEACH

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Abstract

This paper describes field measurements of near-surface hydraulic gradients within a sandy beach during individual swash cycles. We show several different types of behaviour which may have implications for swash zone sediment transport: (1) measurements of swash depth; (2) 'unloading' events with large upward-acting hydraulic gradients; (3) infiltration events with smaller downward-acting hydraulic gradients; (4) situations where the probes lower in the bed measure significantly lower heads than the probe at the surface, leading to strongly downward-acting hydraulic gradients; and (5) measurements in the capillary fringe. Large hydraulic gradients, which are more than sufficient to induce fluidisation, occur in the top 15 mm of the bed under swash and backwash. These large hydraulic gradients, which occur only in the very top section of the bed, may coincide with a significant depth of water (up to 40 mm), which suggests the potential for entrainment of the fluidised bed under backwash.

Introduction

Accretion and deposition on the foreshore is a function of the interaction of surface and subsurface flow regimes in the swash zone, and an understanding of the interaction between surface and groundwater flows is necessary to model swash zone sediment transport. Previous research has suggested that infiltration and exfiltration in the swash zone may be important mechanisms in beach profile changes, governing sediment deposition and erosion rates above mean sea level. Much of this work has focused on examining the link between tidally-induced groundwater flows and swash infiltration/exfiltration, with the assumption that changes in swash volume would alter swash/backwash flow asymmetry. However, Turner and Nielsen (1997) identified several other mechanisms by which vertical flow through a porous bed could affect swash zone sediment transport, including an alteration in the effective weight of the surface sediment due to vertical fluid drag and modified shear stresses exerted on the bed due to boundary layer thinning due to infiltration or thickening due to exfiltration.

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It has been suggested by a number of authors going back to Grant (1946, 1948) that groundwater outflow from a beach during the ebb tide may enhance the potential for fluidisation of sand, and thus the ease with which sand can be transported by swash flows. However, groundwater outflow from a beach in response to a falling tide is unlikely to be sufficient to induce fluidisation since hydraulic gradients under the sand surface will tend to be relatively small, generally of the order of the beach slope (1:100 to 1:10). Baird et al. (1996,1997,1998) suggested a different mechanism for the local fluidisation of the sediment bed due to the propagation and release of a pressure pulse into the seepage face during swash. They showed theoretically how hydraulic gradients in the saturated sediment beneath swash can exceed the threshold for fluidisation.

Despite recent measurements of pore water pressures under swash such as those of Turner and Nielsen (1997), there is still considerable uncertainty about the effects of hydraulic gradients on sediment transport mechanisms and rates (Oh and Dean, 1994; Baldock and Holmes, 1998, this volume), and it is important to determine the magnitude of the hydraulic gradients near the surface of the sediment bed in order to identify the nature of the seepage flow within the bed. This paper addresses this point and describes field measurements of the near-surface hydraulic gradients within a sandy beach during individual swash cycles.

Field site and methodology

Field measurements were made on a sandy beach at Canford Cliffs, Poole, England, a groyned beach with a mean slope of 3.2° ($\tan \beta = 0.055$) on the upper foreshore and a mean slope of 1.5° ($\tan \beta = 0.027$) on the lower foreshore. The sand is well-sorted and negatively skewed, with a mean sediment size of 0.24 mm. The mean hydraulic conductivity of the sediment was 0.00225 ms^{-1}, with a range from 0.00036 to 0.01179 ms^{-1}, and a coefficient of variation of 143%, which is typical for this parameter. The beach is backed by a concrete sea wall set in underlying poorly-permeable silts giving no-flow conditions on the inland and lower boundary. The tidal range at Canford Cliffs varies between 0.2 and 2.2 metres on neap and spring tides respectively. The field site is described in more detail in Baird et al. (1998).

Two deployments were undertaken, one in March 1997 and one in October 1997. The March 1997 deployment was conducted on a spring tide, with a tidal range of 1.3 metres. The wave conditions during the March deployment were atypical for this coastline, with long period swell ($T \approx 16$ s, $H_b \approx 0.8$ m) resulting in a swash zone in excess of 30 m width and with little interaction between sequential swash cycles. The October 1997 deployment was also conducted on a spring tide, with a tidal range of 2 metres. Wave parameters seaward of the swash zone were measured with a seabed-mounted pressure transducer located approximately 17.5 m seaward of the swash instruments. All instruments were logged at 4 Hz. The wave conditions in the October deployment were much more typical of this limited-fetch coastline. The significant wave height varied over the measurement period between 0.23 and 0.43 m, while H_{rms} varied between 0.16 and 0.3 m. The peak wave period varied between 3 and 4.7 seconds, and the width of the swash zone varied between 3 and 7 m. The value of the surf scaling parameter ($2\pi^2 H_b / gT^2 \tan^2\beta$) varied between 9 and 16.9, indicating intermediate conditions. Low values of the surf scaling parameter (<2.5) indicate reflective conditions, whereas high values of the surf scaling parameter (>20) are associated with dissipative conditions.

Near-surface hydraulic gradients in the swash zone were measured by a technique developed by Baldock and Holmes (1996). This uses a series of 2 mm internal diameter probes, inserted into the sediment and connected to pressure transducers above the water surface (Figure 1). Pressure variation is transmitted into each probe through twelve 0.4 mm holes drilled into the tip. The probes cause negligible disturbance to the swash flow or the sediment, and may be moved vertically within the bed to compensate for bed level changes over several swash cycles. The whole system may be easily moved to any location on the foreshore and therefore swash zone measurements can be made at different tidal stages. Four probes were deployed with a horizontal spacing of 1 cm (shore parallel) and with a range of vertical spacings (minimum 1 cm). Vertical hydraulic gradients could therefore be obtained within the upper 3 cm of the beach sediment at a single position in the beach.

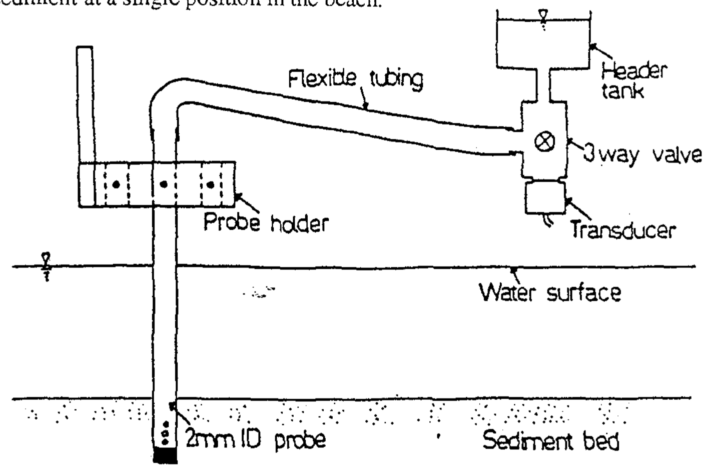

Figure 1. The pressure measurement system.

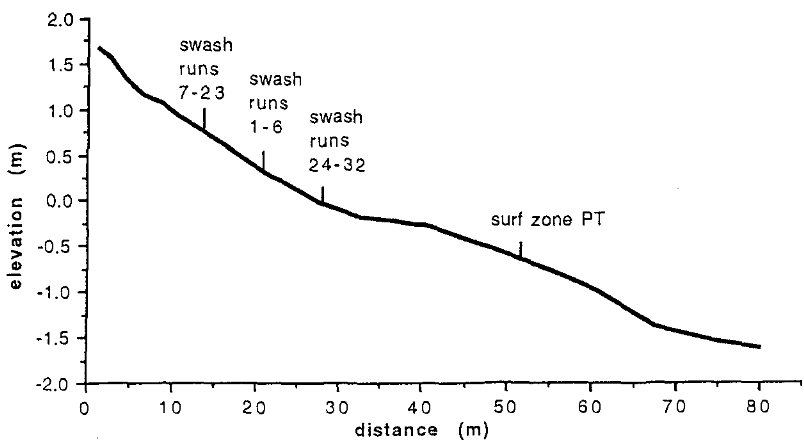

Figure 2. The beach profile and instrument locations on 19 October 1997.

In the October deployment, the spacing between the top probe and the second probe was 11 mm, the spacing between the second probe and the third probe was 11 mm, and the spacing between the third probe and the fourth probe was 10 mm. Measurements were taken with the array at a number of positions, the lowest of which was with the top probe at -65 mm and the bottom probe at -97 mm. However, the most common configuration was with the top probe 5 mm below the surface, and probe 2 at -16 mm, probe 3 at -27 mm and probe 4 at -37 mm. The position of the array was adjusted constantly to ensure that the top probe remained at the surface as the bed level changed. Measurements were made at two positions on the flood tide and one position on the ebb tide (Figure 2); however, only data obtained on the rising tide are shown in this paper. Measurement was begun when the instruments were at the landward edge of the swash zone, and the swash zone moved past the measurement point as the tide rose. Twenty six data sets were collected in March 1997 and thirty-two data sets in October 1997. A selection of the results will be shown here, mainly from the October data. Some results of the March deployment were presented by Baird et al. (1997).

Results

All data are shown as either head (*h*) in mm or hydraulic gradient (*dh/dz*), which is expressed in head units and therefore dimensionless. All pressure readings from the probes were zeroed to hydrostatic pressure with the watertable at the sand surface. In effect, therefore, all probe readings can be converted to length units to give total head values with the surface acting as a datum. Thus, positive values mean that the water level is above the sand surface: in other words, swash or backwash. Negative head values mean the water level is below the sand surface. However, negative heads do not necessarily mean a real negative pressure (i.e. suction). Only if the head value is less than the probe elevation below the surface is there a suction. In the convention used here, a positive hydraulic gradient represents a downward-acting seepage force (infiltration) and a negative hydraulic gradient represents an upward-acting seepage force. The fluidisation criterion adopted here is based on Packwood and Peregrine (1980), who noted that for many sands and fine gravels, fluidisation occurs when the upward-acting dynamic hydraulic gradient is greater than (i.e. more negative than) about -0.6 to -0.7 (in the convention used here).

Figures 3 and 4 show time series of heads 5 mm below the bed surface (in effect the swash depth) for the March and October deployments, respectively. Small changes in the saturated bed level can be seen, indicated by deviations from zero head at the end of the backwash. Wave groups are evident in both diagrams, with little interaction between sequential swash cycles. Despite the difference in the wave conditions on the two deployments, grouping is evident in all of the swash records. Low-frequency swash motions will be directly induced by these wave groups and are probably dominant over standing long waves in this case (Baldock et al., 1997). However, here we are mainly concerned with short wave swash motion.

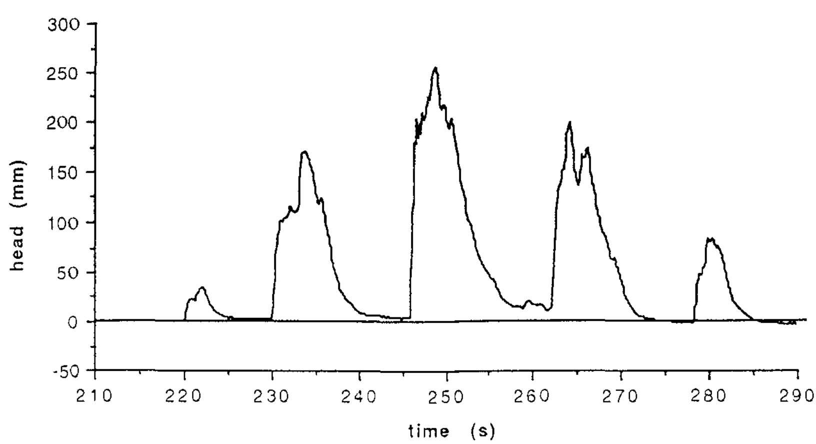

Figure 3. Swash-induced head 5 mm below the bed surface (run 1, 25 March 1997).

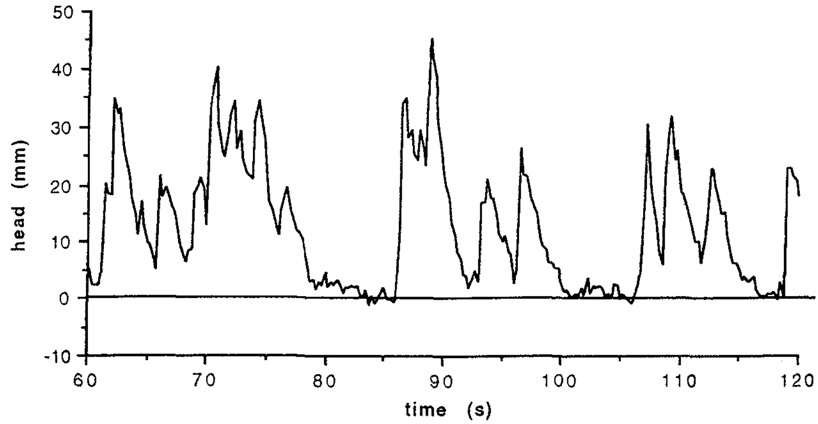

Figure 4. Swash-induced head 5 mm below the bed surface (run 2, 19 October 1997).

Figures 5 and 7 show heads immediately below the surface from the March and October deployments, respectively, while Figures 6 and 8 show the associated hydraulic gradients in the 15-16 mm immediately below the bed surface. Despite the difference in incident wave conditions, a similar phenomenon is observed in both cases (and in many others not shown here). All data were obtained on a rising tide. Similar effects were not observed on a falling tide, where positive hydraulic gradients appeared to dominate. Only very small positive hydraulic gradients (infiltration) were observed during the uprush, while large negative hydraulic gradients (upward flow) were observed at the end of the swash cycle. In both Figures 5 and 7, the head at the top probe (-5 mm) drops more rapidly than the head at the second probe (-15 or -16 mm). This is associated with large negative (upward-acting) hydraulic gradients, as illustrated in Figures 6 and 8. The maximum (i.e. most negative) hydraulic gradient associated with the first case (Figures 5 and 6) is -2.7 and the maximum (most negative) hydraulic gradient in the second case (Figures 7 and 8) is -2.3. In both cases, this is more than sufficient to fluidise the bed, as the fluidisation criterion is a hydraulic gradient of -0.7.

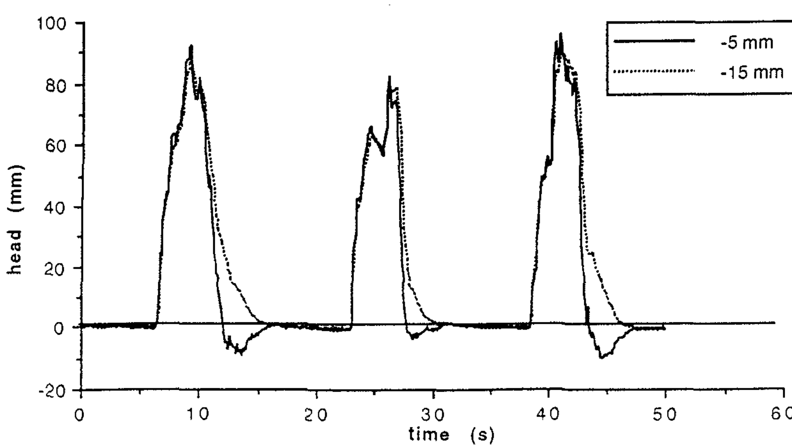

Figure 5. Swash-induced heads at -5 mm and -15 mm (run 12, 25 March 1997).

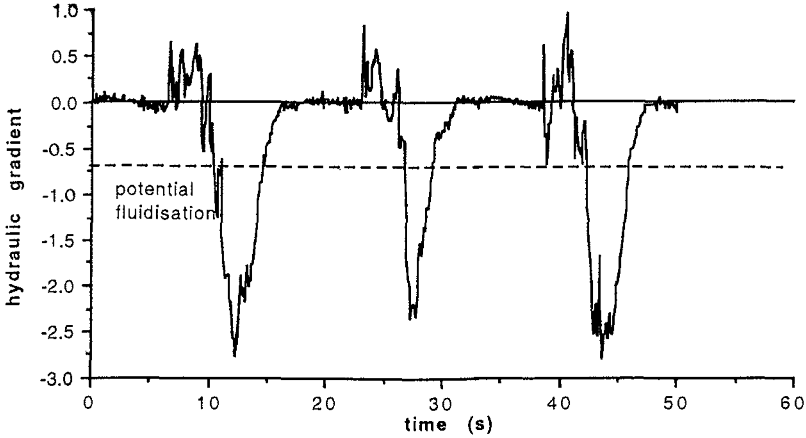

Figure 6. Hydraulic gradients under swash (run 12, 25 March 1997).

These large upward-acting hydraulic gradients appear to be the result of a rapid drop in the head in the upper 15-16 mm of the sediment, which occurs prior to the release of head/pressure deeper in the bed. Although this could indicate suction and hence partial drainage of the sediment, this effect may also be due to the rapid unloading experienced by the sediment as the swash retreats, as suggested by Baird et al. (1996). Suction without drainage could be produced if air trapped in the sediment comes under positive pressures during loading, whereas during unloading the air is no longer under pressure and suction forces develop around the sand grains. However, the unloading occurs on every swash event in the data set from 25 March, whereas it occurs only occasionally in the data from 19 October. The sediment in this region was loosely consolidated and probably had a small but significant air content. Observations on 25 March, when significant cliffing occurred on the beach face and ebullition from the bed was observed, suggested that the air content in the sediment was higher on that day than in October. Also, during the March deployment the longer swash cycles, with very little swash interaction, allowed more time for drainage of the beach between swashes.

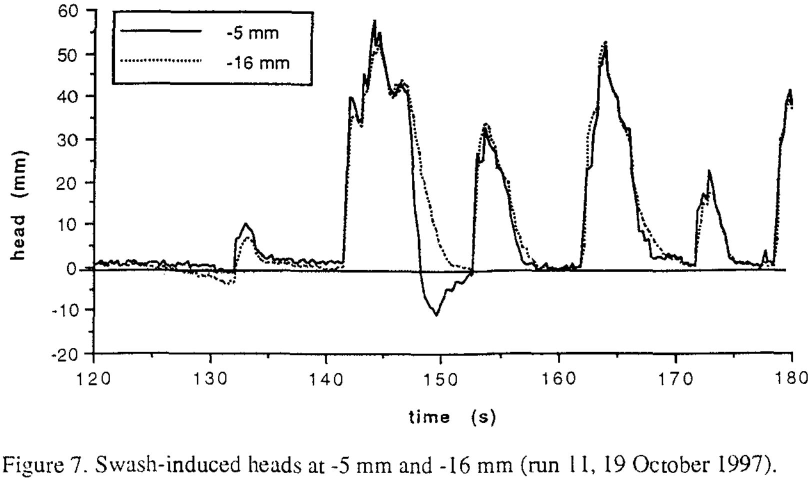

Figure 7. Swash-induced heads at -5 mm and -16 mm (run 11, 19 October 1997).

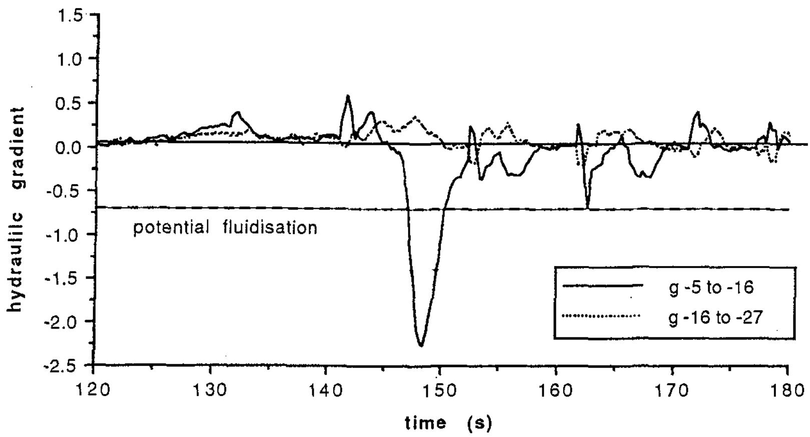

Figure 8. Hydraulic gradients under swash (run 11, 19 October 1997). The solid line is the hydraulic gradient between the probes at -5 and -16 mm. The dotted line is the hydraulic gradient between the probes at -16 and -27 mm.

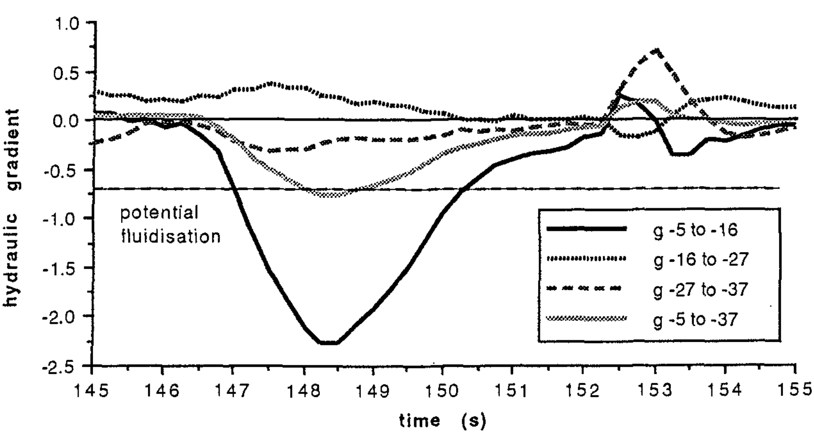

Figure 9. Hydraulic gradients in the top 37 mm of the bed for the 'unloading' event illustrated in Figures 5 and 6 (run 11, 19 October 1997).

Figure 9 illustrates the hydraulic gradients from the same data on 19 October, showing that the extremely large hydraulic gradient associated with the release of pressure as swash retreats occurs only in the top 16 mm of the bed. The hydraulic gradients lower in the bed are much smaller, and are generally not sufficient to fluidise the bed. At deeper depths (-27 to -37 mm) hydraulic gradients were in the range -0.3 to 0.5, which although less than the hydraulic gradients in the top 16 mm, are still considerably in excess of tidal groundwater hydraulic gradients (of order β). As reported by Baird et al. (1997), in some of the data, gradients in the sand bed were observed to be acting both downwards and upwards at the same time. For example, in the section of the record shown in Figure 9, the hydraulic gradient between -16 mm and -27 mm is positive (downward), whereas all of the others are negative. (The hydraulic gradient over the whole measurement area, between -5 mm and -37 mm, which is also negative, is only included on Figure 9 to show that if the sensors had been further apart, a much smaller hydraulic gradient would have been measured and much useful information would have been lost.) There are a number of possible explanations for these apparently anomalous results. The beach sediment was probably not uniform with depth, in which case the hydraulic properties of the sediment, such as hydraulic conductivity, packing, or air content would also have varied. There may have been divergent flow because of lags in the system due to changes in specific storage. One of the probes may have had an air bubble, which would have distorted the results. This last reason is unlikely, however, as the phenomenon was observed on many occasions.

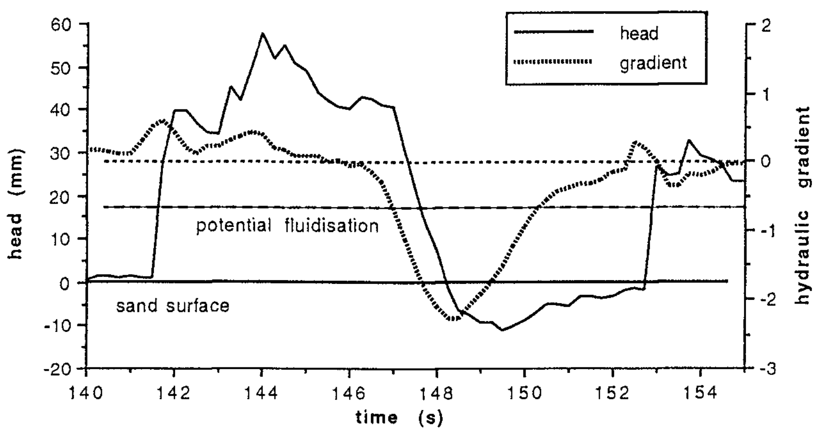

Figure 10. Head at top probe (-5 mm) and hydraulic gradient for the 'unloading' event illustrated in Figures 5,6 and 7 (run 11, 19 October 1997).

Figure 10 shows the swash depth (head at -5 mm) and the hydraulic gradient in the top 16 mm of the bed for the 'unloading' event which occurs between 145 and 155 seconds, which is also illustrated in Figures 7, 8 and 9. The fluidisation criterion is exceeded while a significant depth of swash exists (maximum 40 mm), and exceeds the fluidisation criteria for several seconds while still under swash/backwash. These data also appear to support the hypothesis of Baird et al. (1996,1997,1998), where the large upward hydraulic gradients, sufficient to induce fluidisation of the sediment at the surface, may occur during the latter stages of backwash, thus providing readily entrainable material that can be carried seaward by the backwash flow. Note that this does not necessarily conflict with the findings of Turner and Nielsen (1997). The hydraulic gradients reported here were measured in the top 16 mm of the bed, whereas Turner and Nielsen's top pressure measurement was at a depth of 40 mm. Our data showed strongly negative hydraulic gradients only in the top 1-2 cm of the bed.

Figure 11 shows another example of an 'unloading' event from earlier in the tide on 19 March. The first swash event begins at t≈7s, as the head and water depth rise rapidly. The hydraulic gradient before the swash arrives fluctuates around zero and is mainly just barely positive (and therefore downward-acting), indicating drainage after the previous swash. As the swash depth increases, the hydraulic gradient increases. The hydraulic gradient then begins to decrease as swash depth decreases. However, the hydraulic gradient remains positive throughout this swash event, suggesting infiltration is occurring under both swash and backwash. Between t≈12s and t≈32s, both the swash depth and the hydraulic gradient fluctuate around zero, suggesting conditions similar to those observed by Turner and Nielsen (1997), with the top of the capillary fringe at the sand surface and the phreatic surface fluctuating within this zone of tension saturation. The hydraulic gradient begins to rise at about t≈32s, before the water level begins to drop. At t≈38 s, the hydraulic gradient reaches its maximum and the water level begins to drop rapidly. Between t≈39s and t≈49s, the hydraulic gradient is very slightly positive, while the water level decreases at a slower rate, suggesting less rapid drainage. In this section of the record, the water surface is below the probe, suggesting that it is measuring pressures/heads in the capillary fringe. The next swash arrives at t≈49 s and the water level rises almost instantaneously. The hydraulic gradient becomes negative for the first second of this swash event, and then rises until t≈53s, when it begins to fall. Just before t≈54s, the swash reaches its maximum depth and the hydraulic gradient becomes negative (upward-acting). Between t≈54s and t≈56s, the hydraulic gradient is less than (i.e. more negative than) -0.7 (sufficient to induce fluidisation of the bed), reaching the most negative value of -1.2 while there is still a significant depth of water in the backwash (30 mm). Throughout the time that the swash depth is decreasing, the hydraulic gradient remains negative, suggesting upward flow at the end of the swash/backwash cycle. However, as in the previous examples, the very large upward-acting hydraulic gradient is only measured in the top 16 mm of the bed. The upward-acting hydraulic gradients lower in the bed are much smaller, between -0.1 and -0.5. The swash depth reaches zero at t≈56s; at this time the hydraulic gradient is increasing, but still negative. The hydraulic gradient does not become positive again until t≈59s. Both the depth and the hydraulic gradient then fluctuate slightly around zero until the next swash arrives at t≈77s.

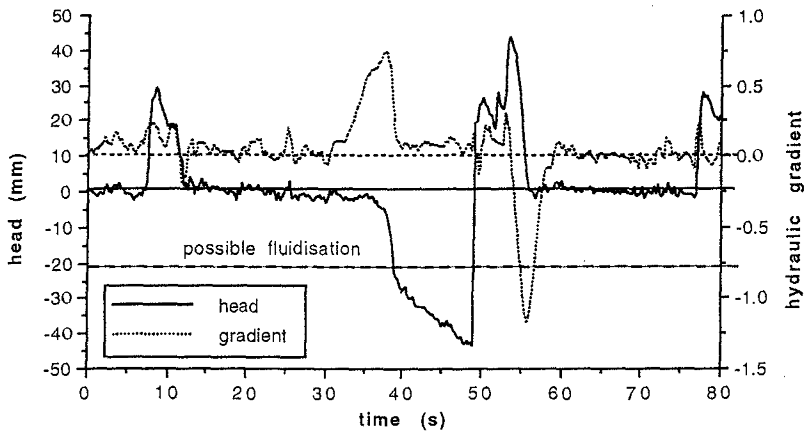

Figure 11. Head at top probe (-5 mm) and hydraulic gradient (run 8, 19 October 1997).

Another phenomenon can be seen in the portion of this data set where infiltration is occurring, between t≈32s and t≈49s, which is associated with a hydraulic gradient of 0.7. This is illustrated in Figure 12, which shows the head at the top probe (-5 mm) and the bottom probe (-37 mm). Although the head measured by the surface probe does not begin to drop until t≈38s, the head measured by the bottom probe begins to decrease several seconds earlier, at t≈32s. At t≈40s the two probes are again measuring the same head, which they continue to do for the rest of the infiltration event. The reason why the bottom probe drops off before the top one is not clear. There may be several explanations for this time lag between the pressure drop at the top and bottom probes. These data were collected when the saturated sand surface was moving back and forth past the measurement point. One possibility, based partly on our ideas and a suggestion from Nielsen (pers. comm.), who suggested that the formation and destruction of meniscuses between sediment particles could cause the pressure at the bottom probes to drop before the pressure at the top probe, is that there is a thin 'tongue' of fully saturated sediment (i.e. no meniscuses) propagating within the sediment. This thin totally saturated zone, just below the bed surface, may influence the pore pressure within sediment that is not quite fully saturated (i.e. a capillary fringe where meniscuses are present). This tongue of full saturation may propagate in advance of swash or may be formed due to small amounts of swash infiltration. Below this saturated zone, the sediment is likely to be less than fully saturated due to drainage between sequential swashes. A second fully saturated zone is then reached at the tidally-induced watertable elevation. The observed head difference occurs between the top probe and the bottom three probes, over only a few centimetres of the beach material, which suggests that the subsurface layer of full saturation is quite thin.

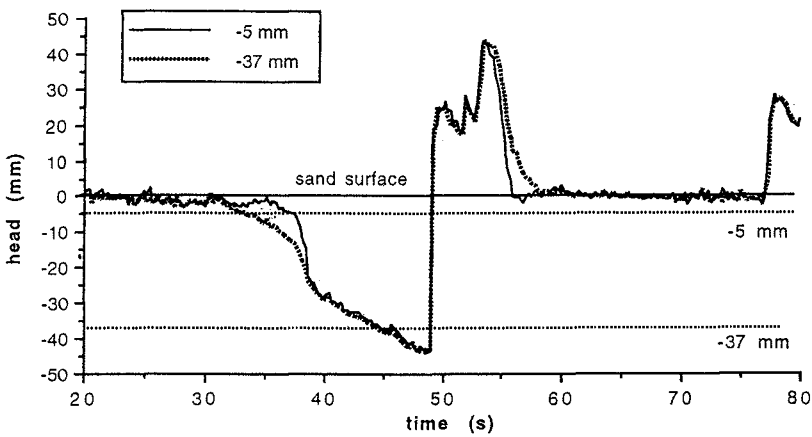

Figure 12. Head at top and bottom probes (run 8, 19 October 1997).

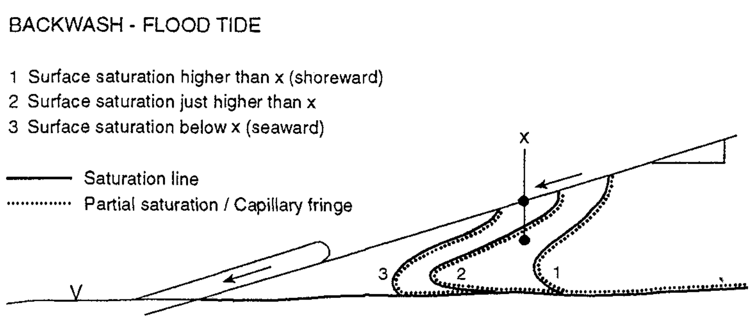

Figure 13. Possible configuration of subsurface water under backwash on a flood tide.

Figure 13 illustrates a possible configuration of this subsurface water under backwash on a flood tide. At time 1 (equivalent to the period before t≈32s on Figures 11 and 12), the position of the saturated surface is shoreward of the measurement point, and both probes are within the saturated tongue and measuring virtually the same head. At time 2 (t≈32s), the tongue has moved downslope. The bottom probe is no longer in the tongue, whereas the top probe is. Therefore the bottom probe measures a lower head than the top probe. At time 3 (before t≈40s) the tongue has moved further downslope and neither probe is in it. After this, the head measured at both probes decreases at the same rate due to natural drainage of the beach. This continues until the next swash arrives (before t≈49s).

Figure 14 illustrates a situation similar to that described by Turner and Nielsen (1997), showing rapid groundwater response to swash, with a near instantaneous rise followed by a slower rate of decline. Large watertable fluctuations (>80mm) can be seen under relatively shallow swash flows (<20mm). In this data set, the top probe is at -15 mm and the bottom probe is at -47 mm. At the beginning of the record, the apparent water level is below the elevation of both probes and they are measuring 'real' negative pressures, suggesting both are in the capillary fringe. The uprush arrives at the measurement point at t≈286s and the head at both probes rises instantaneously, although the head measured by the bottom probe does not rise as much. Both probes are measuring positive pressures, but they are not measuring the same head of water. Between t≈287s and t≈298s, the head decreases at both probes, suggesting a falling local watertable. However, throughout this period the top probe continues to register a higher head than the bottom probe. The two probes measure the same head and decrease at the same rate for a brief time after t≈298s, until at t≈300s the next swash arrives and the same pattern recurs. The head rises instantaneously at both probes as the swash arrives, but the bottom probe again registers a lower head than the top probe. On this second uprush, however, the discrepancy between the heads measured at the top and bottom probes only lasts for about 2 seconds. From t≈301s both probes measure the same head again. The reason for the differences in head measured by the top and bottom probes is not totally clear, but could be due to downward vertical drainage, which would give lower heads at depth. After backwash, infiltrated water will tend to drain downwards and seawards, and even though such drainage may be minimal and short-lived, it should be sufficient to give rise to the differences in heads observed.

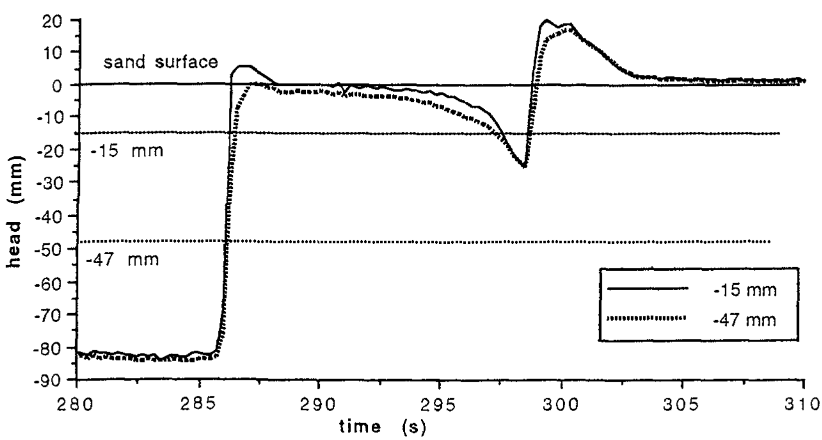

Figure 14. Head at top and bottom probes (run 20, 19 October 1997).

Figure 15 shows the head measured at the top probe and the hydraulic gradient between the top probe (-15mm) and the bottom probe (-47 mm) for the same event as Figure 14. The times when the top and bottom probes are measuring different heads are associated with large positive (downward-acting) hydraulic gradients, suggesting infiltration into the beach. However, it is also possible that the observations illustrated in Figure 14 could be explained by the thin sloping tongue of fully saturated sediment hypothesised earlier. Figure 16 illustrates a possible configuration of this tongue under uprush on a flood tide, which could correspond to the conditions shown in Figure 14.

At time 1 (corresponding to the period before t≈286s in Figure 14), the uprush has not reached the measurement point, and both probes are in the partially saturated zone or capillary fringe and measuring the same heads. At time 2 (t≈286s), the uprush has just reached the measurement point. The bottom probe is not yet in the fully saturated layer and therefore measures a lower head of water than the upper probe. At time 3 (t≈298s and t≈301s), the uprush and the fully saturated layer have moved past the measurement point and both probes measure the same head of water. After this, the head measured at both probes decreases during the backwash and then due to natural drainage of the beach. This continues until the next swash arrives.

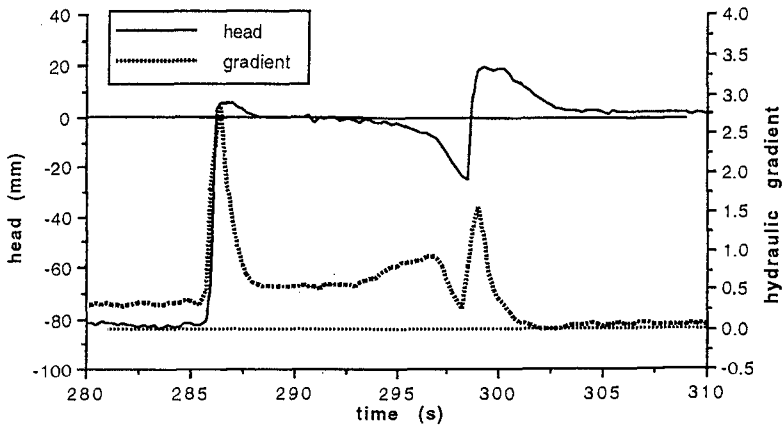

Figure 15. Head at top probe (-15 mm) and hydraulic gradient (run 20, 19 October 1997).

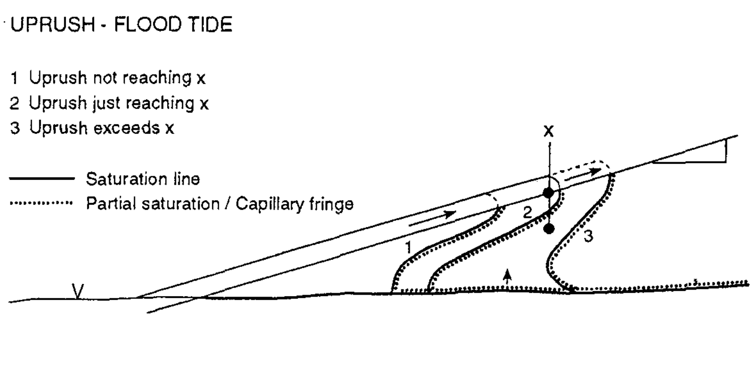

Figure 16. Possible configuration of subsurface water under uprush on a flood tide.

Figure 17 shows a longer time series of the same record (run 20, 19 October 1997). Even larger fluctuations can be seen than in Figure 14 (>90mm) under shallow swash (<20mm). On several occasions (starting at t≈110s and t≈236s), the uprush does not reach the measurement point; however, the head at the top and bottom probes rises, although suctions still persist at both probes. Although in these cases the probes are not measuring pressures under swash, they still appear to be measuring pressure changes related to swash motions. We interpret this as pressures in the not fully saturated zone or capillary fringe being influenced by pressure changes around its boundaries as groundwater moves up the beach in response to swash. Again, Figure 16 illustrates the possible saturation levels but, in this instance, neither the swash or the total saturation line reach the measurement position. The pressure in a medium which is not fully saturated appears to respond in the same way as the watertable. In the event beginning at t≈110s, both probes are in the capillary fringe and are measuring real negative pressures (suction), as the water level is below the elevation of the probes. In the event beginning at t≈236, the top probe is measuring a real negative pressure and is thus in the capillary fringe. The water level is slightly above the elevation of the bottom probe, so the bottom probe is not in the capillary fringe. At other times (t≈75s, t≈187s, t≈202s, t≈286s and t≈299s), the uprush reaches or very nearly reaches the measurement point. In these cases, a situation similar to that shown in Figure 14 is observed, where the head rises instantaneously at both probes as the swash arrives. However, the bottom probe measures a lower head than the top probe, again suggesting that the sediment is not fully saturated. This situation occurs on each of these events and is associated with positive (downward-acting) hydraulic gradients of between 1.1 and 2.8. Note that the long time scale between individual swashes reaching the measurement point is due to wave grouping effects. This leads to large amplitude low-frequency fluctuations in the pressure just below the sand surface (which may also occur deeper in the bed). However, these pressure fluctuations are not due to long wave pressure pulses propagating through the beach material, but are simply due to the intermittent nature of the pressure forcing toward the landward limit of the swash zone.

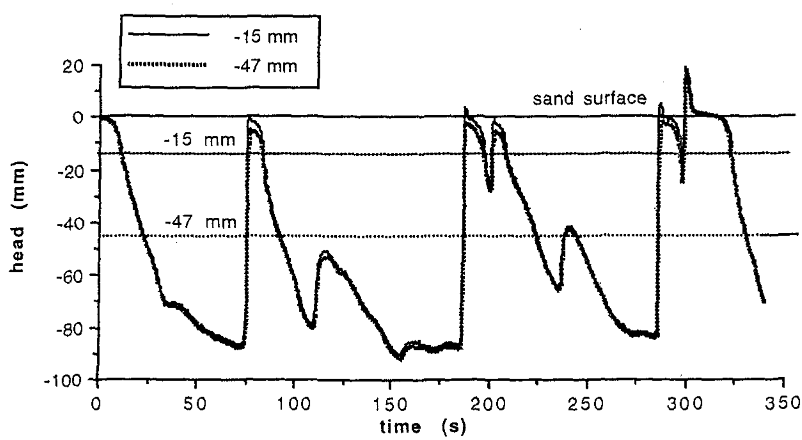

Figure 17. Head at top and bottom probes (run 20, 19 October 1997).

Conclusion

Field measurements of near-surface heads and hydraulic gradients within a sandy beach during individual swash cycles have been presented. The hydraulic gradients measured under swash are considerably larger than the hydraulic gradients produced by tidal groundwater motion. The data shown here demonstrate several different types of behaviour which may have implications for swash zone sediment transport: (1) measurements of swash depth; (2) 'unloading' events with large upward-acting hydraulic gradients: (3) infiltration events with smaller downward-acting hydraulic gradients; (4) situations where the probes lower in the bed measure significantly lower heads than the probe at the surface, leading to strongly downward-acting hydraulic gradients; and (5) measurements in the capillary fringe. Of particular note is the situation when large hydraulic gradients, which are more than sufficient to induce fluidisation, occur in the top 15 mm of the bed under swash and backwash. These large hydraulic gradients may coincide with a significant depth of water (up to 40 mm), which suggests the potential for entrainment of the fluidised bed under backwash. The fact that these large upward-acting hydraulic gradients occur only in the very top section of the bed highlights the importance of measuring pressures very close to the sand surface. The results also indicate that regions which are fully and less fully saturated appear to develop below the sand surface, particularly a thin layer of totally saturated sediment which moves up and down the beach with the swash. This suggests that very small changes in the amount of water in the sediment can lead to large differences in heads, which highlights the importance of knowing more about the saturation characteristics of the bed.

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