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Rapid water table fluctuations within the beach face: Implications for swash zone sediment mobility?

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Abstract

To incorporate groundwater infiltration/exfiltration in the description of swash zone sediment transport, it is required that the details of groundwater dynamics within the beach face be clarified. Field measurements of the vertical pore-pressure structure within the bed identify capillarity effects as the primary mechanism driving rapid and relatively large magnitude water table fluctuations within the swash zone. When the upper extent of the fully saturated capillary fringe coincides with the beach face surface, wave runup produces near-instantaneous increase in pore-pressures across the capillary fringe, corresponding to a rapid rise of the phreatic surface (i.e. the surface where pore-pressure = atmospheric pressure) to the sand surface. Therefore, counter to previous conclusions in the literature, the rapid rise and fall of the water table under the swash zone do not equate to regions of the beach face alternating between states that favor sediment deposition (unsaturated) and erosion (saturated). Similar reports that rapid fluctuations of the water table within the beach face correspond to rapid rates of vertical flow and hence bed fluidization, are also a misinterpretation. Field measurements, and a careful consideration of saturation and pore-pressure characteristics within the beach face, demonstrate that rapid water table rise is associated with minute (downwards) swash infiltration, rather than rapid (upwards) groundwater exfiltration. The cause of the pressure fluctuations and phreatic surface oscillations is the alternating appearance and disappearance of meniscuses at the sand surface, which generate pressure head fluctuations of decimeters due to the addition of millimeters of water. © 1997 Elsevier Science B.V.

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1. Introduction

Investigation of the dynamics of coastal groundwater has both practical and research applications to coastal engineering. At the regional scale, the elevation of the water table may dictate foundation and structural design, and an understanding of groundwater flow is critical to water supply and effluent disposal projects in the coastal zone. At the scale of the runup of individual waves across the beach face, the local elevation of the water table and its influence on groundwater infiltration and exfiltration within the swash zone may contribute to accretionary or erosional trends at the shoreline. It is at this latter process scale that the present study is focused.

The physical mechanisms that link beach groundwater and sediment transport are yet to be adequately investigated. It is anticipated that vertical flow through the bed has several important implications to sediment transport in the swash zone. These include: uprush-backwash flow asymmetry resulting from the loss/addition of swash volume (e.g., Grant, 1948; Duncan, 1964), the altered effective weight of surficial sediment due to vertical fluid drag (Ref. Nielsen, 1992), and modified shear stresses exerted on the bed due to boundary layer 'thinning' or 'stretching' (Ref. Sleath, 1984). The suggestion by its proponents that 'beach dewatering' technology (for review, Ref. Turner and Leatherman, 1997) is a viable tool for shoreline stabilization, may be the practical end-point of more basic research questions of groundwater-sediment interactions at the beach face.

Groundwater in the coastal zone is observed to respond to a range of oceanographic and atmospheric forcing. These include: coastal storms (e.g., Clarke and Eliot, 1987), the propagation of shelf waves (e.g., Lanyon et al., 1982), wave setup (Hanslow and Nielsen, 1993), barometric pressure changes (Dominick et al., 1971), and of course, ocean tides. Numerous field studies have described tide-driven groundwater fluctuations in coastal aquifers (e.g., Emery and Foster, 1948; Ericksen, 1970; Lanyon et al., 1982; Turner et al., 1997), and several recent studies have investigated the non-linear characteristics of tidal-groundwater oscillations (e.g., Nielsen, 1990; Kang et al., 1994; Li et al., 1997).

It is less well recognized that groundwater (pore-pressures and/or the phreatic surface) within the beach face can also fluctuate at higher frequencies in response to wave runup. A limited number of field studies have noted oscillations of the water table in the range of incident and infragravitry waves frequencies (Bradshaw, 1974; Waddell, 1976; Lewandowski and Zeidler, 1978; Hegge and Masselink, 1991). What is most significant are suggestions in the literature that high-frequency water table fluctuations necessitate that the beach face alternates between saturated and unsaturated states — implying rapid transition between conditions favoring local erosion and deposition — and that rapid rates of water table rise result in bed failure through fluidization. Clearly, if these assertions were correct, then rapid water table fluctuations must be a significant factor contributing to the mobilization of sediment within the swash zone.

The objectives of this study are to present field measurements of rapid pore-water pressure fluctuations within the beach face beneath the swash zone, and to elucidate the physical mechanisms that results in this rather striking phenomenon. Particular emphasis is given to a careful re-evaluation of the significance of this behavior to sediment mobility in the swash zone.

2. Field measurements

2.1. Field sites

Field measurements of the vertical structure of pore-water pressures within the beach face were obtained at two barrier island sites on the US Atlantic coast (see Fig. 1): the US Army Corps' of Engineers Field Research Facility (FRF) at Duck, North Carolina, and Assateague Island National Seashore, Maryland. Experiments were undertaken at both sites as part of a wider investigation of groundwater dynamics within the beach face, swash infiltration/exfiltration, and implications for sediment transport.

The data presented here were obtained at the Assateague Island field site. The beach face during the field deployment was planar and essentially featureless, with the exception of subtle cusping around the elevation of high tide. The beach face exhibited a relatively low gradient ($\tan \beta = 0.05$), and is composed of well sorted, medium-fine, quartz sediment (mean grains size $\overline{D} = 0.4$ mm). The tide range was approximately 1.0 m, and small waves (breaking wave height $H_b < 0.5$ m, peak period $T_p = 10$ s) spilled though the dissipative surfzone resulting in swash excursions of 3–5 m across the beach face.

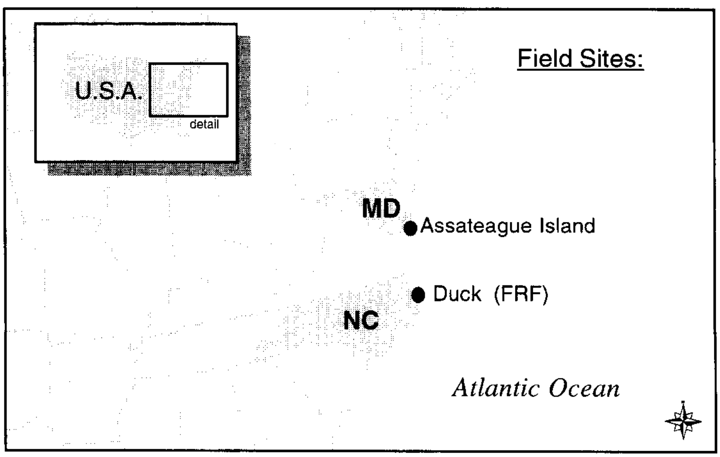

Fig. 1. Field sites.

2.2. Equipment and deployment

High-sensitivity, low-range, vented pressure sensors (manufactured by *Keller PSI*, model 46S) were buried directly within the beach face. Direct burial eliminates the need to consider the frequency-response characteristics of conventional well points or screened piezometers. The sensors were calibrated for full-scale response over the gauge-pressure range corresponding to −300 mm to +700 mm of hydraulic head. To exclude the mechanical force of sand grains from impinging on the sensing diaphragm, a 40 μm stainless steel screen was mounted over the relatively large (25 mm diameter) pressure port. The void between the diaphragm and protective screen was filled with silicon oil, that remained in place with the sensors buried in an inverted orientation. The frequency response of the sensors sampled at 8 Hz was effectively instantaneous.

To monitor rapid water table fluctuations within the swash zone, three buried sensors were mounted in a vertical array on a light aluminum frame. Sensor spacing was set at 150 mm, and the frame buried by augering so that the top-most sensor was located 30 ± 10 mm below the surface of the bed. The absolute elevation of the vertical sensor array remained fixed, local erosion and deposition accounted for the ± 10 mm depth range through a tidal cycle.

Incident waves were monitored by a single pressure transducer located in the mid surfzone, approximately 20 m seaward of the shoreline. All sensors were cabled to a single PC, logging at 8 Hz for 17 min ($n = 8192$) bursts.

2.3. Results

The data presented here were obtained during a single data collection run on 23rd May 1996, at the Assateague Island site. These time-series of pore-pressures within the bed are characteristic of the data obtained from both field sites. The buried vertical

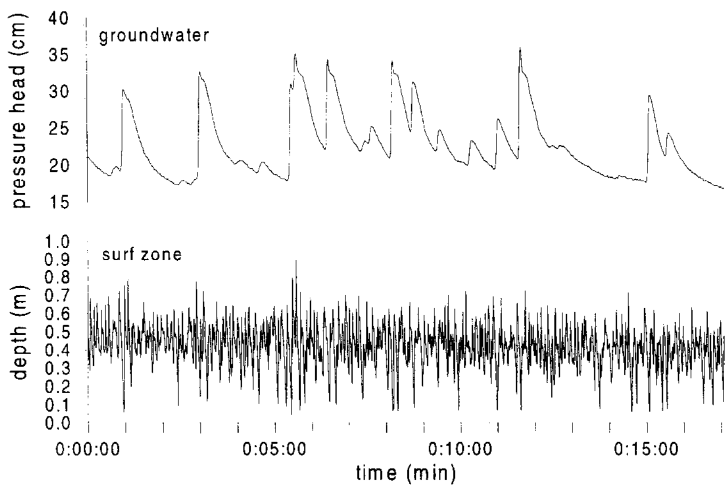

Fig. 2. Bottom buried sensor and surf zone time-series; Run#9 5/23/96.

sensor array was located in the mid-intertidal profile during tidal ebb. At both field sites, rapid water table fluctuations in the swash zone were most evident during falling stages of the tide, following submergence then re-emergence of the beach face where the sensors were buried. The most rapid and large magnitude oscillations were observed when the tide had fallen to the point where only the largest swashes reached the elevation of the sensors, with the majority of swashes extending 2–5 m seaward of this location.

Fig. 2 shows simultaneous time-series recorded by the bottom buried sensor ($z = -340$ mm) and the surfzone transducer. The two pressure signals have been converted to hydraulic head and water depth respectively. The most striking feature of this groundwater behavior is the large magnitude of observed pore-pressure fluctuations. Pressure head within the bed oscillates by up to 15 cm, in disproportion to the fact that this response was induced by over-topping of the buried sensor array by the very upper limit of wave uprush, and therefore swash depths of at most a few centimeters. It is apparent that groundwater response is rapid, with each fluctuation event characterized by near-instantaneous rise, followed by a somewhat slower rate of decline.

A further interesting feature of these time series is that, although groundwater within the beach face is clearly responding to wave runup, this does not occur at the frequency

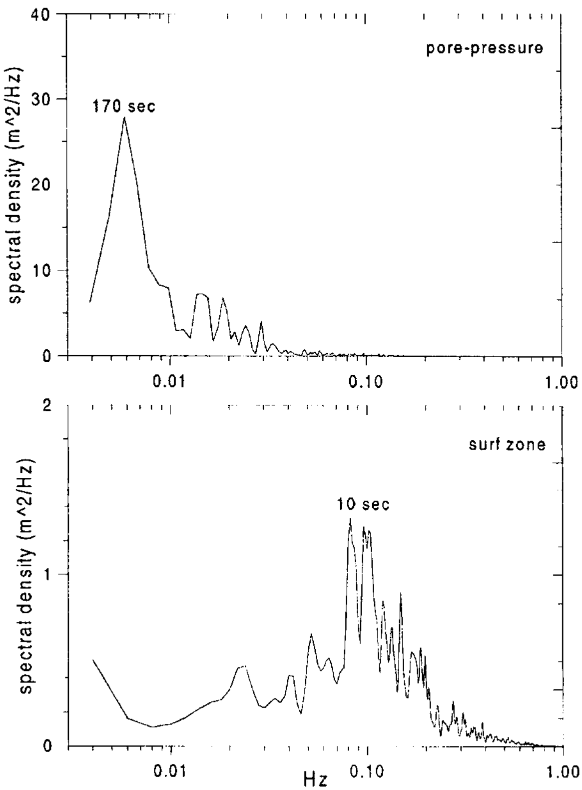

Fig. 3. Comparison of groundwater (upper panel) and surfzone (lower panel) spectra.

of individual waves. This is further demonstrated in Fig. 3, which contrasts the spectra of rapid groundwater fluctuations (upper panel) and the mid surfzone water-level (lower panel). The surfzone spectrum contains a clear peak centered around incident wave frequencies (0.10 Hz or 10 s), consistent with the presence of both locally generated seas and longer swell waves. In contrast, the groundwater spectrum exhibits a broad peak around 0.006 Hz. Note that this peak also does not correspond to a secondary peak in the wave spectra around 0.02 Hz, characteristically associated with infragravity oscillations of the surf zone water-level. It is speculated that this indicates that pore-pressure response to wave runup is modulated by the meniscus drainage characteristics of the beach face, that appears to occur at a slower rate than long-period surf zone oscillations. This hypothesis is currently the focus of further investigation.

3. Analysis

It is a common misconception that fluctuating pore-water pressures monitored at a single depth equate to the same magnitude rise and fall of the water table within the bed. This is not the case, unless pore-water pressure remains hydrostatic ($\partial p/\partial z = -\rho g$). As will be shown later in Section 3.3, this condition is in fact met for the field measurements presented here. It is therefore correct to conclude that the water table beneath the swash zone was rapidly fluctuating up to 15 cm in elevation. However, prior to discussing in detail the observed vertical structure of beach face pore-pressures, it is instructive to first clarify the concepts of bed fluidization and capillarity.

3.1. Bed fluidization

It is hypothesizes by several authors (e.g., Bradshaw, 1974; Chappell et al., 1979) that rapid water table fluctuations at the beach face may cause bed failure due to instantaneous fluidization. The condition of a fluid bed results when the destabilizing force of upwards fluid drag exceeds the stabilizing force of gravity. In studies of vertical flow within the sea bed induced by unbroken surface waves in the nearshore, flow out of the bed has been referred to as 'bed ventilation' (Conley and Inman, 1992). In hydrology, forces exerted in the direction of flow on individual grains within the bed are referred to as 'seepage forces', and the condition of fluidization at the surface is commonly know by terms such as 'piping' (e.g., Dunne, 1988) 'seepage erosion' (e.g., Hutchinson, 1968) or 'groundwater sapping' (e.g., Higgins, 1984). An interesting coastal engineering perspective of bed fluidization is proposed by Gourlay (1980), who notes that failure results when the rate of upwards-directed vertical flow exceeds the fall velocity of sediment at maximum concentration.

The stress exerted normal to the bed due to the exfiltration of groundwater across the beach face is proportional to the vertical pore-pressure gradient, and can be simply determined for a unit volume of the bed. For a vertical flow velocity w, the total force F_z acting on a volume V of the bed of bulk density ρ_b is given by the sum of the seepage pressure gradient and gravity

$$F_z = -\rho_b gV + \frac{w}{K}\rho gV \tag{1}$$

where K is the hydraulic conductivity of the bed, g is gravitational acceleration and ρ is fluid density. The seepage force F_s per unit volume is

$$F_s = \frac{w}{K}\rho g \tag{2}$$

and the condition for fluidization of the bed is given by

$$w_{crit} = K\left(\frac{\rho_b}{\rho} - 1\right) \tag{3}$$

corresponding to $F_z = 0$ in Eq. (1).

In Fig. 4 an estimate of the critical fluidizing velocity defined by Eq. (3) is plotted for the range of sand grain sizes (0.1–2.0 mm). Hydraulic conductivity was calculated from sediment characteristics by the empirical formulation of Krumbein and Monk (1942), assuming well sorted sands. It is apparent that, for the full range of fine to coarse sediment sizes comprising sandy beaches, the exfiltration of groundwater within the swash zone at velocities in excess of 5 cm/s is sufficient to cause bed failure. For medium to fine sediments ($\overline{D} < 0.5$ mm), the critical velocity at which bed fluidization occurs is much lower, and groundwater outflow at less than 0.5 cm/s is anticipated to result in failure at the beach face.

Contrast this conclusion with measured rates of water table rise shown in Fig. 5. In the lower panel the rapid pressure-head fluctuations shown previously in Fig. 2 are again plotted, but now the vertical axis is scaled to indicate water table elevation relative to the sand surface. In the upper panel the corresponding rate of water table rise and fall is indicated. It is apparent that the large pore-pressure pressure fluctuations observed within the beach face were associated with the water table rising to the sand surface at times with speeds in excess of 10 cm/s. If such rapid water table rise were indeed associated with upwards vertical flow (as has been speculated), then clearly the conditions for bed fluidization are met. However, a careful reconsideration of the

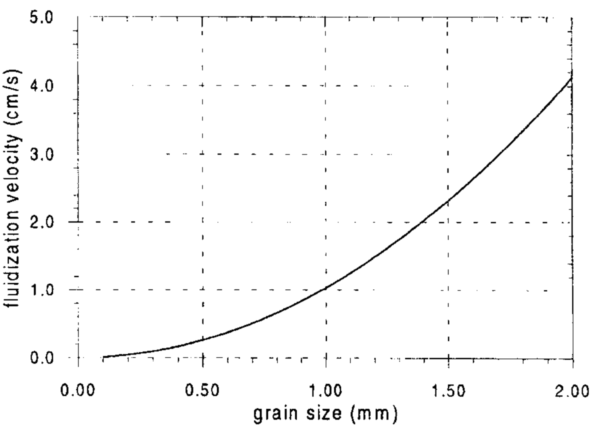

Fig. 4. Critical fluidizing velocity.

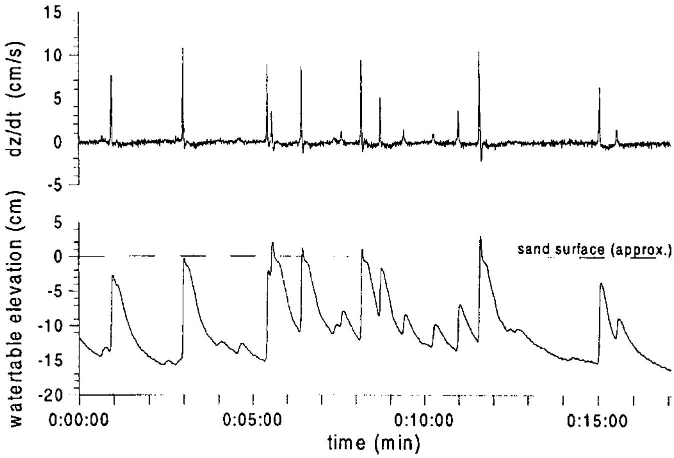

Fig. 5. Rate of water table rise and fall.

moisture and pressure distribution within the beach face provides an alternative and physically more correct interpretation of these data.

3.2. Fundamental groundwater concepts – capillarity

To elucidate the physical mechanism that underlies the groundwater behavior depicted in Figs. 2 and 5, it is necessary to clarify a number of fundamental groundwater concepts. These are basic in the field of hydrology, and can be found in both popular introductory and more advanced texts (e.g., Freeze and Cherry, 1979; Fetter, 1994; Bear, 1979).

The *phreatic surface* (or 'water table') is the surface where pore-pressures are equal to atmospheric pressure (see Fig. 6A). Below this, pore-pressures are of course greater than atmospheric, and excluding trapped air pockets, inter-granular voids are saturated. The *vandose zone* is the moist region above the phreatic surface. In this region pore-pressures may be less than atmospheric due to *capillarity* (surface tension + molecular attraction), and saturation characteristics are variable. Most important to this study, the *capillary fringe* defines the region immediately above the phreatic surface that is completely saturated, the only distinction between this and the saturated region below the water table being negative (gauge) pressures.

The height of capillary rise within the tension-saturated capillary fringe is proportional to surface tension, and inversely proportional to the density of interstitial water and pore size. The rise h_c of a fluid of density ρ in a capillary tube of radius R is given by

$$h_c = \frac{2\sigma \cos\alpha}{\rho g R} \tag{4}$$

where σ is the surface tension of the fluid and α is the angle of the meniscus with the capillary tube. As a first approximation, if cubic packing is assumed of spherical grains

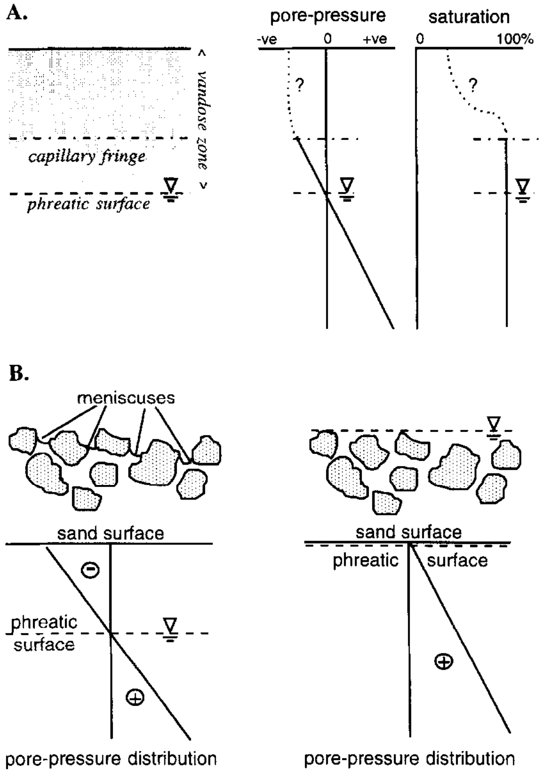

Fig. 6. Definitions and concepts. (A) The only distinction between the regions immediately above and below the phreatic surface (water table) is pore-pressure, both regions are 100% saturated. (B) A macro-scale view of meniscus formation and destruction at the sand surface (after Nielsen et al., 1988).

of uniform diameter D, the equivalent radius of pore spaces is simply $D/5$, and therefore a first estimate of the thickness B of the capillary fringe within the beach face is

$$B = \frac{10\sigma}{\rho g \overline{D}} \tag{5}$$

Capillary rise estimated by Eq. (5) is plotted in Fig. 7 for the range of sand grain sizes. In fine sediments ($\overline{D} < 0.1$ mm) capillary rise of over 70 cm is anticipated, in contrast to capillary rise of less than 5 cm in coarse sands ($\overline{D} > 1$ mm). In medium-fine beach sands, corresponding to the sediment characteristics at the Assateague Island field site, the thickness of the capillary fringe is anticipated to be of the order of 15–20 cm.

The existence of a well developed capillary fringe within sandy beaches has been confirmed by field measurements (Turner, 1993). In particular, it was observed that this saturated region became most pronounced within the beach face during tidal ebb, due to 'stretching' above the falling water table. This is consistent with the theoretical and experimental results of Childs and Pulovassilis (1962) who determined that the tension-

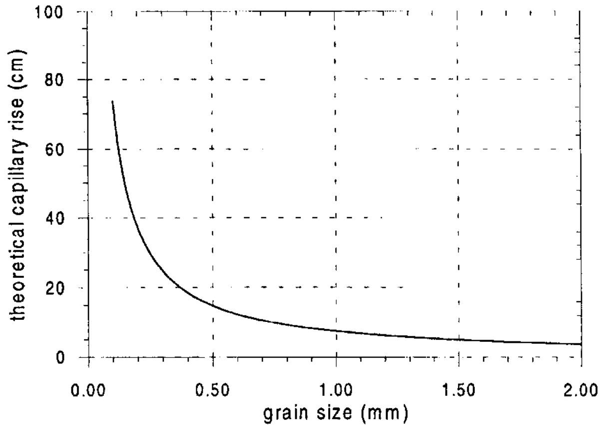

Fig. 7. Theoretical capillary rise (assume $\sigma = 0$).

saturated zone thickens during water table fall. It is the existence of this region of saturated sand *above* the phreatic surface that provides a physical explanation for the groundwater behavior illustrated in Figs. 2 and 5.

3.3. Rapid exfiltration vs. minute infiltration

The role of capillarity effects in determining the rapid rise within the swash zone of the phreatic surface to the sand surface is clarified when the vertical structure of pore-pressure fluctuations is examined. Fig. 8 depicts time-series of simultaneous pore-pressure fluctuations measured by the top and middle buried sensors, in addition to the bottom sensor. The three sensors were located at respective elevations of −40 mm, −190 mm and −340 mm, relative to the sand surface.

With decreasing depth the magnitude of pore-pressures of course decreases, corresponding to the equilibrium hydrostatic pressure gradient within the beach face. However, the magnitude and trend of pore-pressure fluctuations at all three sensor elevations are essentially identical. The most striking feature to observe in this figure is the rapid and recurring pressure reversal recorded by the top sensor. As the phreatic surface fell, pore-pressures initially declined to zero and then became increasingly negative, indicating that the top sensor during these periods was located within the tension saturated zone (i.e. capillary fringe) above the water table. When the vertical sensor array was over-topped by the next large swash, pore-pressure reverted to $p > 0$, as the phreatic surface again rose rapidly towards the sand surface. The pressure record obtained by the middle sensor indicates that it was located just below the elevation to which the water table was repeatedly declining, with pore-pressures approaching but never falling below $p = 0$.

Rapid and seemingly disproportionate rise of the water table within the swash zone results from the special case situation of the upper extent of the capillary fringe coinciding with the sand surface. In simple physical terms, rather than rapid water table rise being associated with rapid (upwards) vertical flow, the observed groundwater

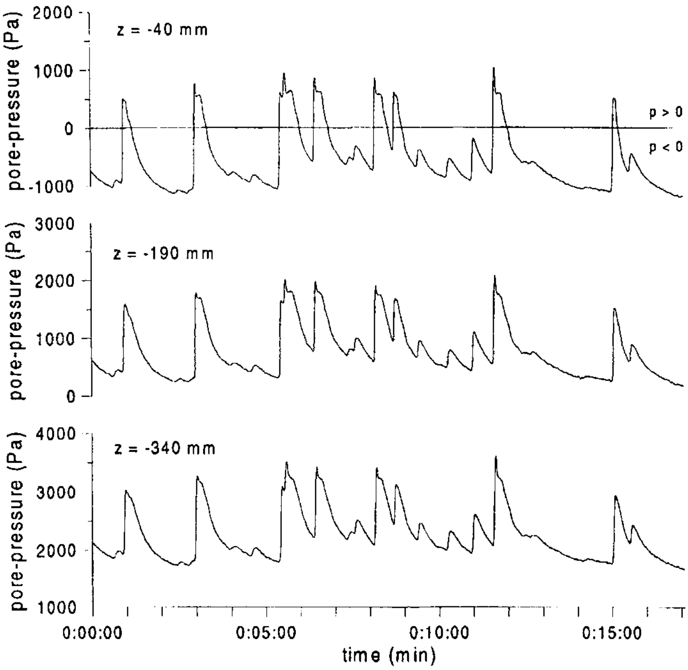

Fig. 8. Vertical structure of pore-pressure fluctuations.

behavior instead results from a near-instantaneous jump in pore-pressures through the entire capillary fringe. The saturation characteristics within this region of the beach face remain unchanged, but instead the $p = 0$ surface simply oscillates within the zone of tension saturation, in response to wave-overtopping. Gillham (1984) used the term 'reverse Wieringermeer effect' after Hooghoudt (1947) to refer to the analogous response of shallow water tables to precipitation.

Simple visual evidence of the moisture/pressure distribution within the beach face can be seen on any sandy beach by observing the changing appearance of the sand surface in response to single swashes. Immediately following wave run-down, the beach face commonly appears slick or 'glassy', but rapidly the upper boundary of this visible 'wet' region moves seaward to a lower and relatively stationary position. What is being observed is the near-instantaneous rise of the phreatic surface to the sand surface across the region where the capillary fringe coincides with the beach face, followed by a slower rate of decline as pore-pressures within the tension-saturation zone revert to less than atmospheric. The upper boundary of the visible slick zone distinguishes the *exit point*, or time-varying point on the beach face where the phreatic surface intersects the sand surface. The stationary elevation to which the exit point repeatedly falls following wave run-down is the 'steady state' elevation of the water table-beach face intersection, corresponding to fully developed meniscuses in the top most grain layer (see Fig. 6B).

It is clear that previous suggestions in the literature that rapid water table fluctuations result in regions of the beach face alternating between 'wet' and 'dry' (presumably

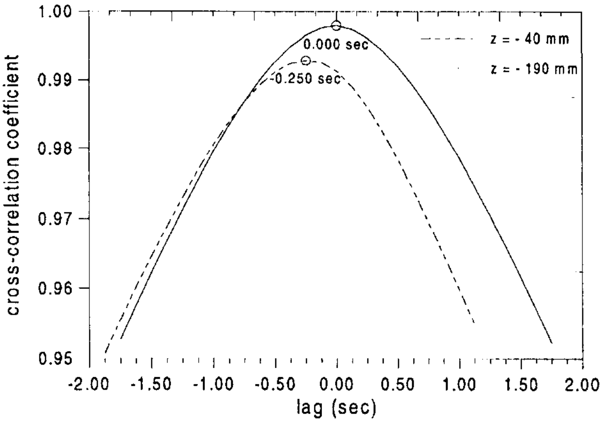

Fig. 9. Cross-correlation between bottom and top, and bottom and middle sensors.

saturated and unsaturated) are incorrect. Further consideration of the field data also demonstrates that it is a misinterpretation to conclude that rapid water table rise corresponds to rapid rates of (bed fluidizing) vertical flow. Fig. 9 presents the results of cross-correlation between the bottom sensor pore-pressure data and the simultaneous time-series of pore-pressures obtained at the elevations of the middle and top sensor. An extremely high degree of correlation is evident in both cases ($r^2 > 0.99$), demonstrating near perfect correspondence. Zero time lag is evident between the bottom and middle sensors, but a time lag of 0.25 s is evident between the bottom and top sensors, indicating that fluctuating pore-pressures at the surface led corresponding pressure fluctuations within the bed. As vertical flow occurs in the direction of decreasing fluid potential (i.e. Darcy's Law), this lag indicates infiltration rather than exfiltration at the surface.

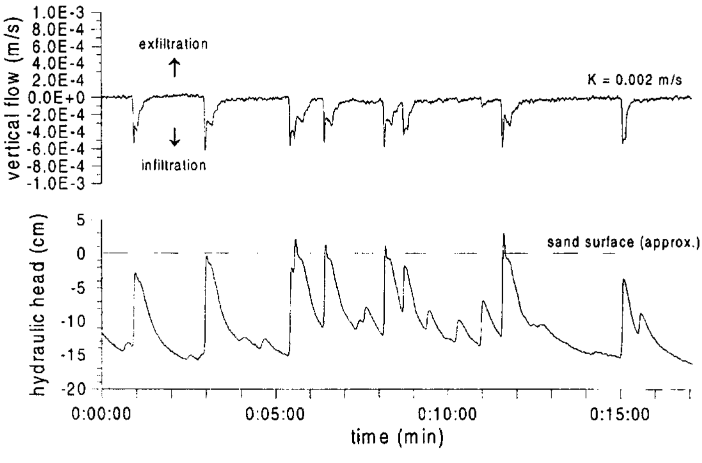

Fig. 10. Calculated infiltration/exfiltration at the beach face.

The fact that rapid water table rise within the swash zone results from minute downwards infiltration, rather than itself inducing rapid upwards vertical flow, is further demonstrated in Fig. 10. In this figure, pore-pressure recorded by the bottom buried sensor is again expressed as hydraulic head, indicating water table rise and fall. Assuming laminar (Darcian) flow, the vertical pressure gradient measured between the middle and top sensors was used to determine instantaneous vertical flow through the beach face. Again, the empirical results of Krumbein and Monk (1942) were used to estimate beach face hydraulic conductivity from sediment size and sorting characteristics, determined by sieve analysis. As anticipated, swash infiltration (of the order of 10^{-4} m/s) coincides with the observed near-instantaneous and large magnitude rise of the phreatic surface to the sand surface.

Finally, it is intriguing to note that, rather than rapid water table fluctuations within the beach face being associated with an increase in sediment mobility, the opposite may be the case. Nielsen (1992) proposed a modified Shields parameter θ_w that includes the effects of swash infiltration–exfiltration

$$\theta_w = \frac{\tau_w}{gD[(\rho_b - \rho) - \rho(w/K)]} \tag{6}$$

where τ_w represents shear stress in the presence of through-bed flow. From Fig. 10, $w/K \approx 0.2$, corresponding to a 12% increase (refer to Eq. (1)) in the effective weight of the sediment. Through a typical sediment transport model with transport $Q_s \sim \theta^{1.5}$, if the effects of boundary layer thinning are ignored this suggests an approximate 20% decrease in sediment transport. The importance of swash infiltration–exfiltration to sediment transport across the beach face warrants further investigation.

4. Conclusions

To incorporate groundwater infiltration/exfiltration in the description of swash sediment transport, it is a necessary precursor that the details of groundwater dynamics within the beach face be clarified. The field measurements presented highlight the importance of capillarity effects to groundwater response at the time-scale of single-wave runup. The existence of a zone of saturated sand (the capillary fringe) above the water table, and in particular the special case of this region coinciding with the sand surface within the swash zone, results in the observed and rather striking phenomenon of rapid and large magnitude fluctuations of the phreatic surface. Field measurements of the vertical pore-pressure structure with the beach face confirm that, rather than fast water table rise being the cause of rapid (and hence bed fluidizing) *upwards* vertical flow, in fact such groundwater behavior is associated with minute *downwards* infiltration of a portion of the swash lens. Rapid water table rise and fall is the response to a local jump in pore-pressures within the capillary fringe, caused by the alternating appearance and disappearance of meniscuses at the sand surface. Counter to previous suggestions in the literature, saturation characteristics of the bed do not vary at incident or infragravity wave frequencies.

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