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Periodic seepage face formation and water pressure distribution along a vertical boundary of an aquifer

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SUMMARY

Detailed measurements of the piezometric head from sand flume experiments of an idealised coastal aquifer forced by a simple harmonic boundary condition across a vertical boundary are presented. The measurements focus on the pore pressures very close to the interface ($x = 0.01$ m) and throw light on the details of the boundary condition, particularly with respect to meniscus suction and seepage face formation during the falling tide. Between the low and the mean water level, the response is consistent with meniscus suction free models in terms of both the vertical mean head and oscillation amplitude profiles and is consistent with the observation that this area of the interface was generally within the seepage face. Above the mean water level, the influence of meniscus formation is significant with the mean pressure head being less than that predicted by capillary free theory and oscillation amplitudes decaying faster than predicted by suction free models. The reduced hydraulic conductivity in this area due to partial drainage of pores on the falling tide also causes a delay in the response to the rising tide. The combined influence of seepage face formation, meniscus suction and reduced hydraulic conductivity generate higher harmonics with amplitudes of up to 26% of the local main harmonic. To model the influence of seepage face formation and meniscus suction a numerical solution of the Richards' equation was developed and evaluated against the data. The model-data comparison shows a good agreement with the behaviour high above the water table sensitive to the choice of moisture retention parameters.

1. Introduction

The interaction between surface and sub-surface water plays an important role in a variety of coastal zone processes including saltwater intrusion and contaminant transport in coastal aquifers (e.g. Cartwright et al., 2004a,b; Cartwright and Nielsen, 2001a,b, 2013; Isla and Bujalesky, 2005; Nielsen, 1999; Nielsen and Voisey, 1998; Robinson et al., 2006; Turner and Acworth, 2004; Xin et al., 2010) and beach profile morphology (e.g. Emery and Foster, 1948; Grant, 1946, 1948). Oceanic forcing of coastal aquifers across the beach face is highly dynamic occurring over a wide range of magnitude and frequency scales (i.e. tide, wave, storm surge, etc.). A number of oceanic and atmospheric mechanisms which have been involved with observed beach water table fluctuations identified by Turner (1998). The majority of studies have described beach groundwater fluctuations due to tidal forces (e.g. Emery and Foster, 1948; Ericksen, 1970; Lanyon et al., 1982; Nielsen, 1990; Turner, 1993a; Turner et al., 1997). A limited number of studies have observed wave-induced the beach water table oscillations (e.g. Bradshaw, 1974; Cartwright et al., 2002, 2006; Hegge and Masselink, 1991; Kang et al., 1994; Lewandowski and Zeidler, 1978; Turner and Nielsen, 1997; Turner and Masselink, 1998; Waddell, 1973, 1976, 1980). Understanding the behaviour of this periodic boundary condition is thus important for accurate modelling of coastal groundwater dynamics and associated issues.

Existing analytical models of ground water dynamics are based on the one or two-dimensional solution of the Boussinesq equation under the Dupuit–Forchheimer assumption, (e.g. Baird et al., 1998; Li et al., 2002; Nielsen et al., 1997; Nielsen, 1990) with corrections for vertical flow effects and also capillary fringe effects by only considering the additional water mass above the water table (e.g. Barry et al., 1996; Cartwright et al., 2005; Li et al., 2000; Nielsen and Perrochet, 2000; Nielsen and Turner, 2000). None of the analytical models consider unsaturated flow or seepage face and meniscus formation at the boundary.

In the natural system, the interface between surface and groundwater is generally sloping; however, in order to simplify

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the problem, a vertical interface is considered here. This paper presents detailed measurements of the piezometric head close to the vertical interface ($x = 0.01$ m) of a non-shallow laboratory aquifer forced by simple harmonic oscillations. The data provides insight into the influence of meniscus suction and seepage face formation in and around the inter-tidal zone. The data is then used to evaluate a 2D vertical numerical model based on the Richards' equation (Richards, 1931) with due consideration of the mixed periodic boundary condition to simulate the formation of the seepage face and meniscus suction.

2. Capillary suction and seepage face formation on the interface

Fig. 1 provides a schematic illustration of the pressure distribution along a beach face when the water table exit point becomes decoupled from the ocean level. Note similar scenarios will exist in systems with periodic forcing of groundwater systems such as tidal rivers and lakes where seiching may occur. When decoupling occurs, two distinct pressure zones become apparent. Below the exit point and above the ocean level (i.e. in the seepage face), the surface has a glassy appearance indicating that the water table is at the surface and that the gauge pressure $p(x, z) = 0$. Above the exit point, the surface has a matt appearance due to the presence of meniscuses and as such $p(x, z) < 0$.

The capillary suction gets stronger with increasing elevation above the water table, but upwards of a certain level this suction will not have a significant effect on water table dynamics due to a lack of connectivity in sand with low moisture content and hence very low permeability. Some a priori insight into vertical and horizontal flow in the capillary fringe might be gained from the steady flow study of Silliman et al. (2002).

Several numerical and experimental studies have been conducted which consider the exit point location and seepage face formation. Turner (1993b, 1995) adapted a numerical model from the governing equations of Dracos (1963) to simulate exit point movement across a saturated beach face. The model is based solely on the force balance on a water particle at the sand surface and neglects the sub-surface pressure distribution. In addition, Turner (1993b, 1995) assumed that, during the decoupled phase, the movement of the exit point is independent of the tide level.

Clement et al. (1994) developed a 2D finite-difference algorithm to solve Richards (1931) variably saturated flow equation for porous media which was then applied to solve steady state and transient seepage face problems. Clement et al. (1994) used three kinds of boundary conditions including Dirichlet boundary condition for nodes with known pressure head, Neumann boundary condition for nodes where the values of normal fluxes are known and a seepage face boundary condition. During simulation of the variably saturated flow, the length of seepage face is unknown until the problem is solved; however, the problem cannot be completely solved unless the length of seepage face is determined. Hence, an iterative process is needed to determine the seepage face length at each time step. Clement et al. (1994) used Cooley (1983) modified version of Neuman (1973) iterative-search procedure which is based on the following. During the first iteration, an initial guess of the location of the exit point (i.e. the length of seepage face) is used to solve the flow equation. Based on the solution's results for pressure head and flow along the boundary, it is possible to understand whether the location of exit point is correct or it needs modification. One of three different conditions may exist. First, the solution gives a zero pressure and a net outflow for all nodes along the seepage face which means that the guessed location of exit point is correct. The nodes above the seepage face are considered as a no-flow boundary condition with negative pressure. Second, if the results show non-zero inflow for some of the nodes along the seepage face which have zero pressure, the height of exit point is overestimated. Third, if some of the nodes above the seepage face which are located on no-flow boundary condition get positive flux, the height of the seepage face is underestimated. The seepage face height is then adjusted as required and the flow equation solved again with the new interface pressure profile. This iterative method is repeated until finding the correct length of the seepage face is produced. This model was later validated by

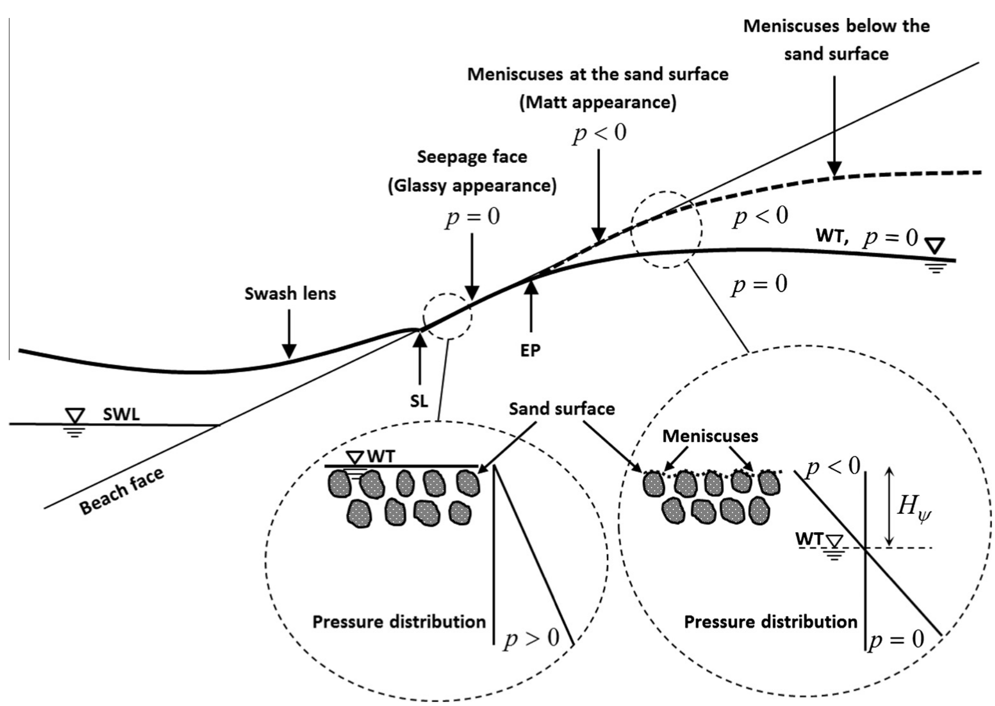

Fig. 1. Schematic illustration of seepage face and meniscuses formation on the beach face. SL = shoreline (swash front); EP = water table exit point; WT = water table; p = pore pressure; H_ψ = steady capillary fringe thickness. Solid and dashed lines represent the free surface and idealised meniscuses surface, respectively (after Cartwright et al., 2006).