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Research papers

Two-dimensional vertical moisture-pressure dynamics above groundwater waves: Sand flume experiments and modelling

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A B S T R A C T

This paper presents a new laboratory dataset on the moisture-pressure relationship above a dispersive groundwater wave in a two-dimensional vertical unconfined sand flume aquifer driven by simple harmonic forcing. A total of five experiments were conducted in which all experimental parameters were kept constant except for the oscillation period, which ranged from 268 s to 2449 s between tests. Moisture content and suction head sensor pairings were co-located at two locations in the unsaturated zone both approximately 0.2 m above the mean watertable elevation and respectively 0.3 m and 0.75 m from the driving head boundary. For all oscillation periods except for the shortest ($T = 268$ s), the formation of a hysteretic moisture-pressure scanning loop was observed. Consistent with the decay of the saturated zone groundwater wave, the size of the observed moisture-pressure scanning loops decayed with increasing distance landward and the decay rate is larger for the shorter oscillation periods. At the shortest period ($T = 268$ s), the observed moisture-pressure relationship was observed to be non-hysteretic but with a capillary capacity that differs from that of the static equilibrium wetting and drying curves. This finding is consistent with observations from existing one-dimensional vertical sand column experiments. The relative damping of the moisture content with distance landward is higher than that for the suction head consistent with the fact that transmission of pressure through a porous medium occurs more readily than mass transfer. This is further supported by the fact that observed phase lags for the unsaturated zone variables (i.e. suction head and moisture content) relative to the driving head are greater than the saturated zone variables (i.e. piezometric head). Harmonic analysis of the data reveals no observable generation of higher harmonics in either moisture or pressure despite the strongly non-linear relationship between the two. In addition, a phase lag of moisture content relative to the suction head was observed indicating that the response time of the moisture content to watertable motion is greater than that of the pore water pressure. The observed moisture-pressure dynamics are qualitatively reproduced using a hysteretic Richards' equation model. However, quantitative differences exist which are likely to be due to previous findings that demonstrated that the Richards' equation model is unable to accurately reproduce the observed watertable wave dispersion, particularly at shorter period oscillations.

1. Introduction

Watertable dynamics play an important role in a variety of coastal zone processes such as salt-water intrusion and contaminant transport into coastal aquifers (e.g. Xin et al., 2010; Robinson et al., 2006) and beach profile morphology (e.g. Emery and Foster, 1948; Grant, 1946, 1948, Bakhtyar et al., 2011). The influence of the unsaturated zone on watertable dynamics has been examined from a range of perspectives including: application of the Green and Ampt (1911) parameterization of the capillary fringe (e.g. Barry et al., 1996; Li et al., 2000); field investigations (e.g. Heiss et al., 2014); laboratory sand column experiments (e.g. Lehmann et al., 1998; Nielsen and Perrochet, 2000a,b; Stauffer and Kinzelbach, 2001) and numerical studies (e.g. Clement et al., 1994). To date, only a limited number of observations of the moisture-pressure dynamics above an oscillating watertable have been made and all of these have been made using a one-dimensional vertical (1DV) sand column.

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Lehmann et al. (1998) conducted sand column experiments to describe water content variations due to water pressure fluctuations at the bottom of the sand column. Water content and potential were measured at different soil depths and an increase in water content, potential damping and time lag by increasing the distance from the capillary fringe was observed. Damping in watertable dynamics due to hysteresis and a highly asymmetrical response of water content to symmetrical fluctuation at the bottom boundary was also noted. They solved a 1DV Richards' equation using the HYSTFLOW (Stauffer, 1996) code with the Brooks and Corey (1966) formulas for the water retention curves, and a modified Mualem (1984) hysteresis model. The hysteretic model was able to reproduce the measured average water content better than non-hysteretic models. Although the hysteretic simulations for the moisture content and the matric potential were close to measured values in or near the capillary fringe, the hysteretic model underestimated the damping in the water content and the matric potential under highly unsaturated conditions above the capillary fringe. Stauffer and Kinzelbach (2001) also formulated a 1DV model for saturated/unsaturated flow based on Richards' equation and Mualem's (1984) hysteresis model which compared well with their sand column observations of moisture content measured using gamma probes.

Nielsen and Perrochet (2000a,b) measured watertable heights and total moisture content in a sand column subjected to a simple harmonic driving head at the bottom of the column with oscillation periods ranging from 14.5 min to 6.5 h. They observed that the watertable height responded very closely to the driving head while total moisture content varied very little compared with the watertable height. Based on the observed frequency response function of the total moisture content relative to the watertable, Nielsen and Perrochet (2000a,b) proposed a complex effective porosity (n_d) concept which implicitly accounts for any hysteresis effects on watertable motion. The magnitude $|n_d|$ accounts for the damping of the total moisture relative to the watertable motion and the argument ($-Arg(n_d)$) describes the phase shift between watertable height and total water content. They also compared experimental data with numerical results of Richards' equation with van Genuchten model (van Genuchten, 1980) and found that the non-hysteretic Richards' model failed to represent experimental data of watertable height and total water content. Nielsen and Perrochet (2000a,b) suggested that considering hysteresis dynamics can improve the Richards' model results.

Werner and Lockington (2003) modelled the sand column data of Nielsen and Perrochet (2000a,b) using a modified version of HYDRUS 1D (Šimůnek et al., 1998) with the hysteresis algorithms of Parker and Lenhard (1987). Inclusion of hysteresis effects provided an improved model-data comparison (in terms of the watertable frequency response function) than was achieved with a non-hysteretic model. Whilst Werner and Lockington (2003) examined the nature of the moisture-pressure scanning loops numerically, none of the above studies have observed the nature of these loops using a physical model.

Cartwright (2014) conducted sand column experiments to study the moisture-pressure dynamics above an oscillating watertable with periods ranging from 10 s to 12.5 h. Using co-located moisture and pressure measurements, their data show clear formation of hysteretic scanning loops for the longer period while for periods less than 15 min, the observed moisture-pressure dynamics became non-hysteretic. The general slope of the observed scanning loops (the capillary capacity) for the high-frequency periods is close to non-hysteretic van Genuchten (1980) curve with $\beta = 3$ which explained the prediction capability of non-hysteretic Richards' model in previous sand column experiments for high frequency watertable motion (Cartwright et al., 2005).

Cartwright (2014) then used the HYDRUS 1D model (Šimůnek et al., 1998) to solve the Richards' equation numerically in conjunction with the van Genuchten moisture retention curves and the empirical hysteresis model of Scott et al. (1983). Despite known artificial pumping errors associated with Scott's et al. (1983) hysteresis model (Werner and Lockington, 2003), the model was able to qualitatively reproduce the observed scanning loops with only some quantitative discrepancies which are likely due to the uncertainty in assumed model parameters.

All of the above mentioned studies only considered a 1DV sand column system and to date, moisture-pressure dynamics above a two-dimensional vertical (2DV) propagating watertable wave are yet to be studied. This paper aims to fill this knowledge gap and presents a new 2DV laboratory dataset to bring to light insights into the moisture-pressure dynamics above a propagating watertable wave. The data is also used to evaluate the predictive capability of a 2DV hysteretic Richards' equation model.

This paper is organised as follows: Section 2 provides a brief description of the sand column experiments of Cartwright (2014) and new sand flume experiments which are used for model-data comparison. Section 3 describes the numerical model and boundary conditions. In section 4 the model results are compared with the existing sand column and new sand flume laboratory data. Finally, Section 5 summarises the major findings and conclusions.

2. Laboratory experiments

In this paper, the numerical model FEFLOW (cf. Section 3) is evaluated against observations of the moisture-pressure relationship: firstly in a 1DV context using the sand column data of Cartwright (2014) to facilitate an initial model validation and inter-model comparison (Cartwright, 2014 employed HYDRUS 1D); and secondly in a 2DV context against new sand flume data.

2.1. Sand column experiments

For ease of reference, the sand column experiments of Cartwright (2014) are briefly outlined here. A sand column with 1.6 m height and 0.15 m square was subject to simple harmonic forcing at its base,

$$h_o(t) = d + A\cos(\omega t) \tag{1}$$

where h_o is the driving head [L], d is the mean driving head [L], A is the driving head amplitude [L], $\omega = 2\pi/T$ is the oscillation frequency [T^{-1}], T is the oscillation period [T] and t is the time [T]. During 19 experiments all parameters were kept constant except the oscillation period which varied from 10 s to 12.25 h. A summary of experimental parameters is presented in Table 1. Suction head and moisture content were measured using UMS-T5 tensiometers and MP406 moisture probes at two elevations approximately 0.3 m and 0.5 m above the mean watertable elevation.

2.2. Sand flume experiments

2.2.1. The sand flume

New 2DV experiments were conducted in a sand flume 9 m long, 1.5 m high and 0.14 m wide (cf. Fig. 1). The unconfined sand flume aquifer was forced at one end with a simple harmonic driving head (cf. Eq. (1)) acting across a vertical boundary. No-flow boundaries were applied at the bottom and 'landward' end of flume. The sand surface (top) boundary of the aquifer was covered only with loose plastic to avoid dust settlement whilst still allowing free communication with the atmosphere. The sand surface remained dry for all experiments and thus can be considered a