DYNAMIC EFFECTS DURING ALTERNATE INFILTRATION AND DRAINAGE OF UNSATURATED GRANULAR MEDIA (HYDRAULIC RATCHETING) STUDIED USING THE LATTICE BOLTZMANN METHOD

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Summary Dynamic effects in connection with multi-phase flow in soils are often observed experimentally. They generally arise as temporarily delayed changes in the water content or in the outflow. Possible mechanisms leading to such effects during infiltration have not been investigated in detail. Experimental investigations on sand columns have shown that for cyclic hydraulic conditions, i.e. the alternate infiltration and drainage of water, dynamic effects may even result in an accumulation of water within the pore structure, which we denoted as hydraulic ratcheting. A new geophysical method (spatial Time Domain Reflectometry) was used in the experiments leading to new insights of the phenomenon. This cyclic accumulation of water may lead to catastrophic mechanic consequences due to the associated loss of negative pore water pressure with low water contents. A Lattice Boltzmann Method (LBM) for water and air flow with solid obstacles was developed to microscopically investigate hydraulic ratcheting in more detail.

INTRODUCTION

Dynamic effects in connection with multi-phase or unsaturated water flow have been observed often in experimental investigations, which generally arise as temporarily delayed changes in the water content (Topp et al. 1967) or in the outflow (Hollenbeck & Jensen 1998). Most of the experiments conducted were not designed to investigate these effects. They were carried out in order to verify Richards' equation (Biggar & Taylor 1960), to investigate the soil properties affecting soil water characteristics (Elzeftawy & Mansell 1975) or to determine the parameters describing the soil water characteristic curve (Wildenschild et al. 2001). An overview of experiments showing dynamic effects is given by Hassanizadeh et al. (2002). These experimental investigations clearly show that dynamic effects are significant in both granular and fine-grained soils in drainage and infiltration. However, in the literature (cf. Wildenschild et al. 2001, Hassanizadeh et al. 2002) the mechanisms discussed as being the cause of these dynamic effects are focused mainly on drainage. The possible mechanisms for the occurrence of dynamic effects during infiltration or even for cyclic hydraulic conditions, i.e. the alternate infiltration and drainage of water, have not been investigated in detail so far.

EXPERIMENTAL INVESTIGATIONS

In order to determine the soil hydraulic parameters depending on the density, the soil water retention curve and the unsaturated hydraulic conductivity, a column test apparatus was developed to carry out multi-step inflow and outflow experiments on samples 40 cm in height and 19 cm in diameter (Fig. 1 left, cf. Scheuermann 2008). The column is equipped with different measuring devices, including four tensiometers installed in order to measure the matric suction at four different locations along the column. Furthermore, two flat band cables are placed between the pipe and the plastic-bag, which encapsulates the sample. The flat band cables make it possible to measure the spatial distribution of the water content inside the soil sample using a newly developed measuring method called 'Spatial TDR' (Fig 1 right, Scheuermann et al., 2009).

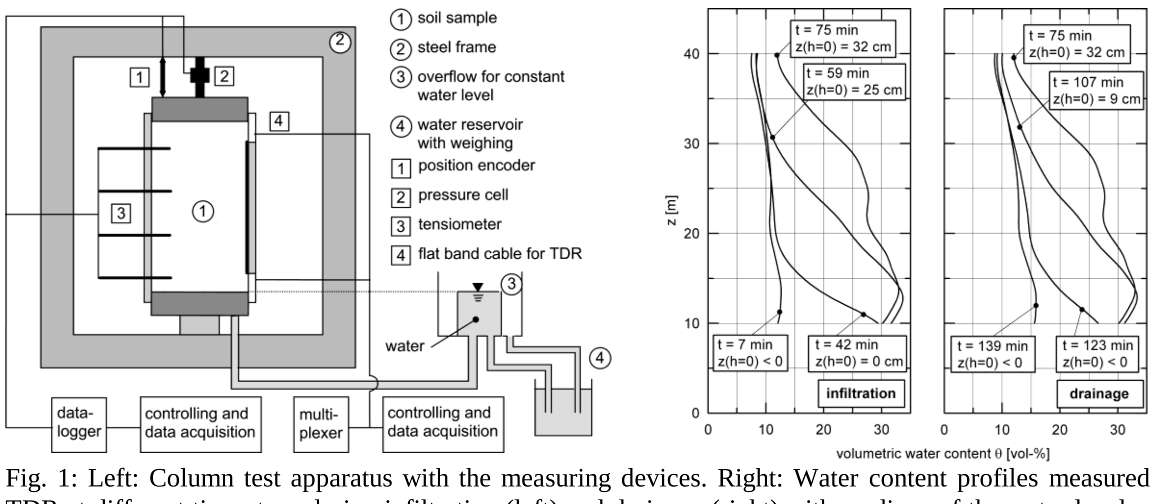

Fig. 1: Left: Column test apparatus with the measuring devices. Right: Water content profiles measured with Spatial TDR at different time steps during infiltration (left) and drainage (right) with readings of the water level measured with tensiometers.

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Altogether four identical hydraulic cycles (infiltration and drainage with four steps each with 2 kPa) were carried out. After each hydraulic cycle, not only the residual hydraulic water content throughout the sample increased, but also the “saturated” water content at the reversal from infiltration to drainage and the water content where the matric suction got lost (transition from negative to positive pore water pressure, Fig. 2 left).

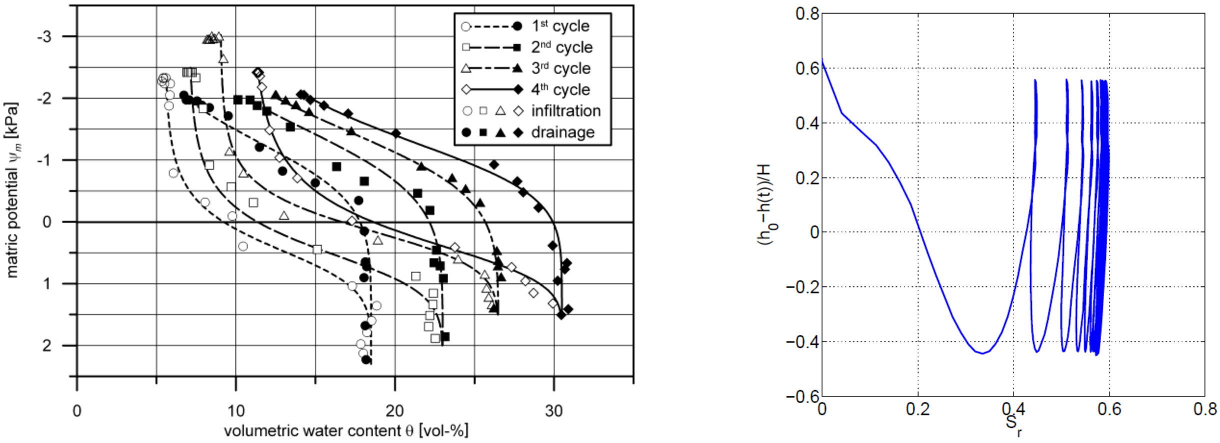

Fig. 2: Left: Measured step-wise increase in the water content inside the soil sample with repeated infiltration of water. Right: Calculated imposed hydraulic head amplitude (h(t)-h0) versus the saturation (Sr) for 16 simulated cycles.

LATTICE BOLTZMANN METHOD

A numerical model based on the Lattice Boltzmann Method (LBM) is proposed to investigate the experimental observations. For the simulations the LBM D2Q9 scheme (Gresho and Sani, 1987) was chosen. In this formalism the space is divided in a square grid and also a discrete set of velocities is assigned to each cell in order to solve numerically Boltzmann’s equation for the fluid. Furthermore, the Multi-Phase (MP) LBM using the Shan-Chan effective potential technique (Shan and Chen, 1993) was used, which includes and attractive force between two adjacent fluid cells controlled by a intensity constant G_a for each fluid. This has been combined with the Multi-Component (MC, Shan and Doolen, 1995) LBM in which a different square lattice is assigned to each component. In our case we considered two components, one denser representing water and one lighter representing air. They are both repelled by a second force which represent inmicisibility defined by a constant G_r. A third force applied to both fluids is gravity characterized by its acceleration value g. Finally, the interaction with solids is divided in two fronts. In one hand the fluid must be repelled by solid cells. For it we have implemented the bounce-back boundary condition (Sukop and Thorne, 2006) for cells that are tagged as solids. In the bounce back condition, after the collision step, the distribution functions are swapped symmetrically producing a complete bounce of the fluid against the solid surface with no slip velocity component. The other front is the capillarity force of attraction, which models real Van der Waals attraction of fluids and soils. This force is controlled by a constant G_s. The three LBM parameters described above (G_a,G_r and G_s) control measurable quantities such as the liquid and vapour densities for each component, the surface tension and the contact angle with solid surfaces. With this model it was possible to qualitatively reproduce the hydraulic ratcheting effect as it was observed in the experimental investigations (cf. Fig. 2 right).

References

Biggar, J.W. & Taylor S.A. 1960. Some aspects of the kinetics of moisture flow into unsaturated soils. *Soil Sci. Soc. Am. Proc.* 24:81-85.

Elzeftawy, A. & Mansell, R.S. 1975. Hydraulic conductivity calculations for unsaturated steady-state and transient-state flow in sand. *Soil Sci. Soc. Am. Proc.* 39:599-603.

Hassanizadeh, S.M., Celia, M.A. & Dahle, H.K. 2002. Dynamic effect in the capillary pressure-saturation relationship and its impacts on unsaturated flow. *Vadose Zone J.* 1:38-57.

Hollenbeck, K.J. & Jensen, K.H. 1998. Experimental evidence of randomness and nonuniqueness in unsaturated outflow experiments designed for hydraulic parameter estimation. *Water Resour. Res.* 34:595-602.

Scheuermann, A., Huebner, C., Wienboer, H., Rebstock, D. and Huber, G. 2010. Fast Time Domain Reflectometry (TDR) measurement approach for investigating the liquefaction of soils. *Measurement Science and Technology*, 21, 2010, doi:10.1088/0957-0233/21/2/025104.

Scheuermann, A. 2008. Water content dynamics in unsaturated soils - Results of experimental investigations in laboratory and in situ, Toll, D., Augarde, C., Gallipoli, D. and Wheeler, S., eds. *Proceedings of Unsaturated Soils - Advances in Geo-Engineering*, Taylor and Francis, 197-203.

Topp, G.C, Klute, A. & Peters, D.B. 1967. Comparison of water content-pressure head data obtained by equilibrium, steady-state, and unsteady-state methods. *Soil Sci. Soc. Am. Proc.* 31:312-314.

Wildenschild, D., Hopmans, J.W. & Šimůnek. 2001. Flow rate dependence of soil hydraulic characteristics. *Soil Sci. Soc. Am. J.* 65:35-48.

Gresho, P. & Sani, R. 1987. On pressure boundary conditions for the incompressible Navier-Stokes equations, *International Journal for Numerical Methods in Fluids*, *7*(10), 1111-1145.

Shan, X. & Chen, H. 1993. Lattice boltzmann model for simulating flows with multiple phases and components, *Phys. Rev. E*, *47*, 1815-1819, doi:10.1103/PhysRevE.47.1815.

Shan, X. & Doolen, G. 1995. Multicomponent Lattice-Boltzmann model with interparticle interaction, *Journal of Statistical Physics*, *81*(1), 379-393.

Sukop, M. & Thorne, D. 2006. *Lattice Boltzmann modeling: An introduction for geoscientists and engineers*, Springer Verlag.