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Hydraulic processes and properties of partially hydrophobic soils: The effect of water repellency on the characteristic curves estimated from dynamic flow experiments

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Abstract

Soil research done over the past decades, has proven that water repellent soils are widespread in all climates. In order to assess the effect of hydrophobicity in the estimated characteristic curves, inflow/outflow experiments were conducted in the laboratory for one soil and two artificial created hydrophobic mixtures. In the inflow/outflow experiments the pressure head at the bottom of the soil column was increased/decreased and the estimated curves were obtained by means of inverse modeling. Multistep inflow/outflow experiments were also conducted using ethanol instead of water in order to estimate the effect of liquid wetting properties on the estimated characteristic curves of the materials under study. The results have shown that the water retention functions and the unsaturated hydraulic conductivity functions estimated from the dynamic experiments are strongly dependent on the degree of hydrophobicity and the wetting/drying process.

Keywords

Water repellency, hydrophobicity, ethanol, Multistep Outflow Experiment, imbibition, drainage

Introduction

Soil research done over the past decades, has proven that water repellent soils are widespread in all climates. The effect of water repellency to soils includes reduced infiltration capacity, accelerated soil erosion, uneven wetting patterns and development of preferential flow (Doerr et al., 2000). It is well known that soil water repellency affects the soil water characteristic curves. For the same value of the matric potential less water is withheld by the soil. Similar effects are valid for the conductivity curve also.

In this study the effect of hydrophobicity on the soil hydraulic properties (SHPs) estimated under dynamic flow experiments was examined. This was achieved by the comparison of the SHPs estimated using ethanol and water.

Material and Methods

In order to examine the effect of soil water repellency (WR) on the SHPs, multistep inflow/outflow experiments were conducted for three soil materials and for two liquids (water and ethanol). Due to lower value of ethanol's surface tension compared to water's surface tension (Ethanol: 22.4 mN m^{-1}, Water: 72.4 mN m^{-1}), ethanol is considered to be a completely wetting liquid, independent of the degree of water repellency (Lamparter et al., 2010).

Starting from a natural soil (Lakwiese subsoil, LS) and adding different amounts of hydrophilic sand treated with dichloro - dimethyl - silane (DCDMS, 100µL/100g sand) we produced two more mixtures with increasing hydrophobic properties. For the first material (M1) we added 7.5% of the hydrophobic sand whereas for the second material (M2) we added 15% of the hydrophobic sand. The contact angles of the three materials were 62° (LS), 77° (M1) and 94° (M2), respectively.

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For all the experiments we used soil columns 7.2 cm in length. At the bottom of the soil column, a porous plate 0.7 cm in length was adjusted. We conducted multistep inflow experiments in initially air dry columns measuring the amount of water/ethanol that entered the soil column. Then, a multistep outflow experiment followed measuring the amount of water/ethanol drained from the bottom of the system soil-porous plate. For the water drainage experiments the evolution of the pressure head inside the soil column was also recorded.

Using inverse modeling of the Richards equation we obtained the dynamic water/ethanol imbibition and drainage curves. For the description of the SHPs the van Genuchten-Mualem (VGM) model was used and for the inverse simulations the Shuffled Complex Evolution (SCE-UA) algorithm was used.

The water retention curves obtained using ethanol and water are not directly comparable. The reason lies on the different values of surface tension. Lower ethanol contents adjust in the porous system when water and ethanol equilibrate at the same capillary pressure. Moreover, the difference in the dynamic viscosity between the two liquids leads to different liquid infiltration rates even at equal liquid contents. We scaled the pressure head of the ethanol retention curve with respect to the capillary equation to account for differences in surface tension. This yields to a factor of 2.5. For the conductivity curves, we used the concept of intrinsic permeability and multiplied the ethanol conductivity values by the factor 1.2 to account for differences in the dynamic viscosity. For more information concerning the scaling procedure the reader should refer to Lamparter et al. (2010).

Results

Figure 1 shows the experimental results for the imbibition of ethanol in an initially dry soil column. The fitting obtained using the Richards equation is also shown in Figure 1. Figure 2 shows the experimental and fitted data obtained when the soil column was drained. Figures 1 and 2 show that Richards equation can describe the imbibition and drainage of ethanol in the LS material very well. Any discrepancies between measured and simulated data can be attributed to missing flexibility of the VGM model.

Figure 3 shows the liquid retention and conductivity curves obtained using ethanol (red color) and water (blue color). The pressure head values of the ethanol retention curves are scaled by 2.5 leading to an effective supply pressure that is the corresponding supply pressure when equal liquid (ethanol and water) contents adjust in hydrophilic porous media. The same was also done for the pressure head values of the ethanol conductivity curves. Moreover, the ethanol, conductivity values have been scaled by the factor 1.2 to account for differences in the dynamic viscosity.

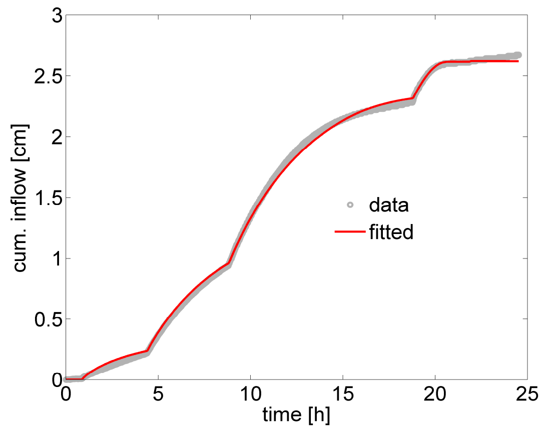

Fig. 1: Measured and fitted cumulative inflow data of ethanol for the LS material.

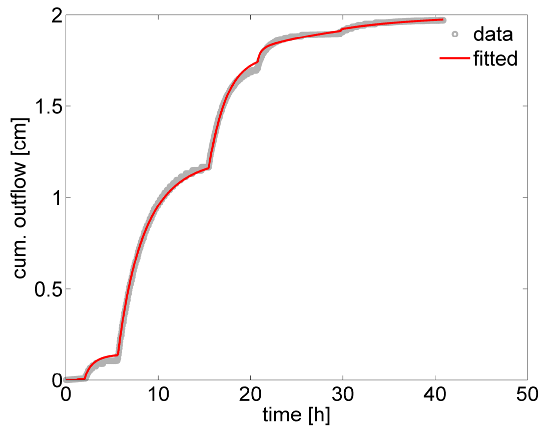

Fig. 2: Measured and fitted cumulative outflow data of ethanol for the LS material.

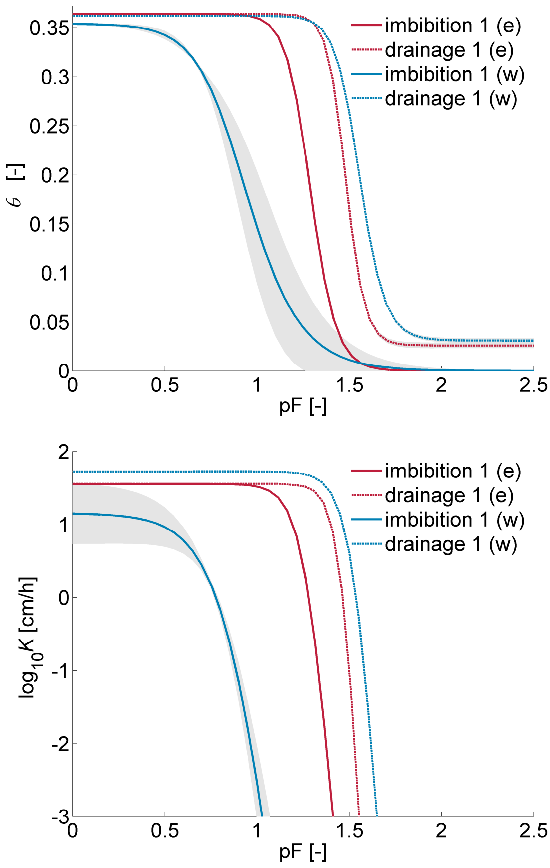

Fig. 3: Liquid retention (up) and liquid conductivity curves (down) for the LS material.

The imbibition and drainage curves of ethanol (red color) in Figure 3 differ significantly. This is due to hysteresis, a very well-known and well-studied phenomenon in porous media. Hysteresis in the capillary pressure versus saturation relationship (or liquid content) is attributed to causes such as the geometric non-uniformity of the individual pores, entrapped air, swelling, and shrinkage (Hillel, 1980). However, Figure 3 shows that the first imbibition curve obtained using water differs significantly from the first imbibition curve obtained using ethanol. For the same pF value more ethanol is retained by the soil, compared with water, indicating a clean effect of WR. The same is also true for the liquid conductivity curve. The LS material had a contact angle of 62 °, and this makes this material partially hydrophobic. On the contrary, for the drainage curve, the curves obtained for both liquids are very close.

Figure 4 shows the estimated curves using ethanol and water for the M1 material in analogous manner as Figure 3 for the LS material. Again the imbibition and drainage curves differ from each other reflecting the effect of “classical” hysteresis. However, for this material we couldn’t estimate the imbibition curve using water, because the M1 material showed extremely high resistance to water.

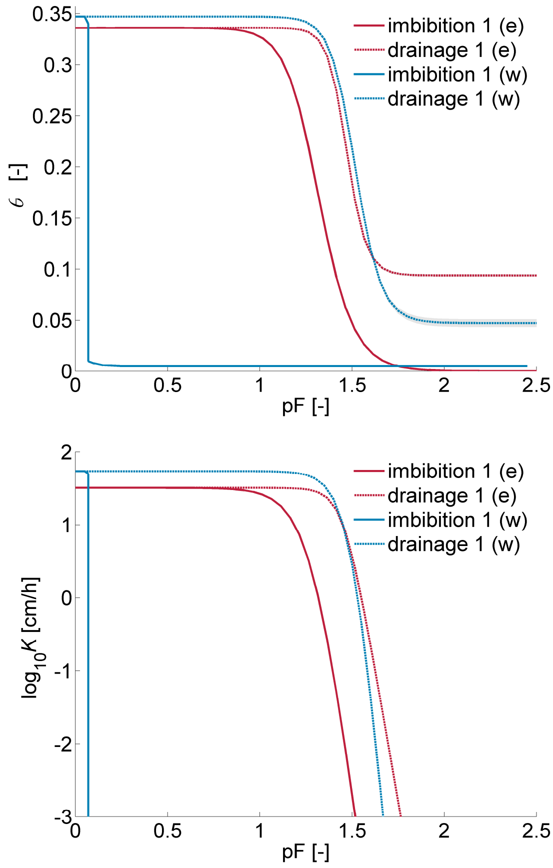

Fig. 4: Liquid retention (up) and liquid conductivity curves (down) for the M1 material (the water imbibition curve is only for illustration reasons and it does not reflect real properties).

Water entered the soil column only when we applied positive pressure at the bottom of the system soil-plate. Water flow inside the soil column appeared in the form of fingers making the applicability of Richard’s equation impossible. For this reason the water retention and conductivity curves (imbibition) in Figure 3 are only for illustration reasons and do not reflect real properties. This shows that WR influences very strong the imbibition of water in the initially air dried soil column. On the contrary, both drainage curves for ethanol and water are extremely close. This indicates that once the porous medium is wetted it behaves as a hydrophilic one. The same is also true for the conductivity curves up to a pF value of around 1.6. For greater pF values the two curves start to deviate and more specific for the same pF value the water conductivity is smaller than the ethanol conductivity. It can be hypothesized that when the large pores empty, water finds an additionally difficulty (hydrophobic grains) to flow compared with ethanol.

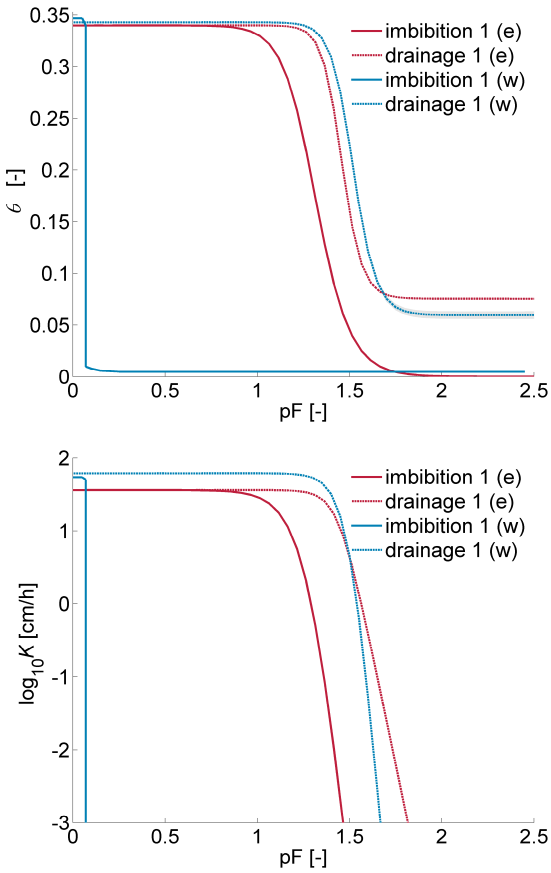

Fig. 5: Liquid retention (up) and liquid conductivity curves (down) for the M2 material (the water imbibition curve is only for illustration reasons and it does not reflect real properties).

Figure 5 shows the estimated curves using ethanol and water for the M2 material. Again, we couldn't estimate the first imbibition curve using water because this material showed also high resistance to water. However, once wetted, the M2 sample had the same hydrophilic behavior as the other two materials although the contact angle of this soil was above 90°. After draining to approximately pF 1.6, when more than half the water was removed from the soil column, the conductivity value of water was again smaller (for the same pF value) compared with the conductivity value of ethanol.

Conclusion

The effect of water repellency on the SHPs estimated under dynamic flow experiments was investigated. This was achieved by conducting multistep inflow/outflow experiments using ethanol and water. The experimental results were treated by means of inverse modeling.

The results show that water repellency influences strongly the imbibition of water in an initially dry material. However, once the material is wetted, then the behavior of the porous medium becomes hydrophilic. For the two artificial created hydrophobic mixtures presented in this study, water repellency had an influence to the hydraulic conductivity curve. Specifically, when significant amount of water was removed by drainage, the hydraulic conductivity values of water became smaller compared with the ethanol conductivity values.

Acknowledgement

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