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Multi-step and two-step experiments in heterogeneous porous media to evaluate the relevance of dynamic effects

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Abstract

The determination of hydraulic properties in non-stationary experiments is suspected to be affected by dynamic effects. This is based on thermodynamic considerations on the pore scale displacement of wetting and non-wetting phase. But also macroscopic heterogeneities at the continuum scale may influence the dynamics of water during drainage and wetting. In this paper we investigate both aspects. Firstly, we present the results of typical multi-step outflow experiments in heterogeneous sand columns which are compared with two-step outflow experiments covering the same pressure range. The discrepancies caused by pressure steps of different size reveal the impact of dynamic effects due to the non-stationarity of the experiments.

Secondly, the influence of macroscopic heterogeneities is investigated based on two-dimensional heterogeneous parameter fields where we compare static hydraulic properties with those obtained from simulated dynamic experiments. These analyses are restricted to numerical experiments because the focus is on the effect of heterogeneities and not on the validity of the applied model (i.e. Richards equation). We found that dynamic effects are not critical neither during the non-stationary experiments nor for heterogeneous parameter fields. This is a positive message for the usage of multi-step outflow experiments to estimate hydraulic parameters. A prerequisite for this clear statement was the introduction of a highly flexible parametrization of the pressure-saturation relation $\psi(\theta)$ which has the only physical constraint to be monotone.

Keywords: Soil hydraulic properties; Dynamic effects; Multi-step-outflow; Unsaturated flow; Spatial heterogeneity

1. Introduction

Hydraulic properties of soil, the soil water characteristic $\theta(\psi_m)$ and the hydraulic conductivity function $K(\psi_m)$, are the basic properties which govern water dynamics in soil. They are based on the state variables of soil water which are the matric potential ψ_m and the volumetric water content θ.

Traditional methods for measuring soil hydraulic properties consider the state variables at static equilibrium [1]. Typically, ψ_m is adjusted and after equilibration θ is measured by different means. Static experiments, however, are time consuming especially in the dry range because of the low hydraulic conductivity and, as a consequence, the long time required to reach equilibrium.

Modern approaches as multi-step-outflow (MSO) are based on transient experiments where the hydraulic state of soil is excited through changing boundary conditions, e.g. jumps in matric potential at the lower boundary in MSO-experiments, and the relaxation towards a new equilibrium state is measured [2,3]. The hydraulic parameters are finally obtained from the inverse solution of Richards

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equation, by which we mean to estimate parameters which minimize a target function characterizing the deviation between simulated and measured values.

Early experiments [4–6] demonstrated that the results obtained from steady state experiments or from static equilibrium differ from those obtained under transient conditions. Generally, compared to the static water potential at a given water content, the water potential during transient conditions is lower during drainage and higher during imbibition. In other words, the water content drags behind the water potential in transient experiments. This phenomenon may cause substantial errors when applying a unique set of hydraulic parameters to different scenarios of water dynamics in soil, which actually is the typical way how hydraulic properties are used. They are considered to be constant material properties.

More recently, the non-uniqueness of hydraulic properties came back to the agenda of research embraced by the notion of "dynamic effects" or "dynamic capillary pressure" [7,8]. Various physical processes can explain the observed phenomena but their relative importance is still not clear. There are mainly two distinct types of explanations for these processes.

One is related to the continuity of the wetting and non-wetting phase during changes in relative saturation [9]. Considering the problem of phase-continuity it was shown by Schultze et al. [10] that close to water saturation the dynamics of drainage can be hampered by the reduced continuity of air. This effect increases water retention and may depend on the size of pressure steps applied in MSO experiments. Large pressure steps may also obstruct the continuity of water which drastically reduces hydraulic conductivity and leads to an increase in water retention as discussed by Wildenschild et al. [11]. They found significant discrepancies between one-step and multi-step experiments in coarse textured soil but not in a soil with a wide pore size spectrum where the formation of discontinuous phases is less pronounced.

Dynamic effects can on the other hand also be explained by thermodynamical considerations of capillary pressure as presented by Hassanizadeh and Gray [12]. In a nutshell, this leads to the understanding that the movement of air–water interfaces requires energy so that the dynamic capillary pressure is always ahead of the static capillary pressure as observed in experiments. To account for this effect Hassanizadeh et al. [7] introduced a dynamic component to the water potential which is proportional to the rate of change in water content $\psi_{\mathrm{dyn}} - \psi_{\mathrm{stat}} \propto -\alpha \mathrm{d}\theta/\mathrm{d}t$. The empirical parameter α is considered to be a material coefficient related to the speed of relaxation towards static equilibrium that may depend on water content. The value of α is estimated from experimental data [7] and hence, it may also contain continuity effects as discussed above.

In this paper, we investigate experimentally the relevance of dynamic effects as postulated by the theory of Hassanizadeh et al. [7] for classical MSO experiments using heterogeneous sand packings. To minimize effects of phase continuity we focus on the secondary drainage branch of the water retention curve and the pressure steps are chosen such that the water phase remains continuous during the experiments. We evaluate how precise two-step outflow experiments can be reproduced by parameters obtained from multi-step experiments. A similar study was made by Hollenbeck and Jensen [13] for homogeneous sand. They compared different one-step and a multi-step outflow experiments and found that the MSO experiment was not well reproducible and that the different one-step experiments yielded significantly different parameters while the deviation from the statically measured water characteristic increased with the size of the pressure step indicating dynamic effects. However, in that study the effects of uncertainties in initial conditions could not be clearly separated from dynamic effects.

Another aspect which is always an issue for the determination of hydraulic properties is the spatial heterogeneity of the material. Apart from pore-scale effects also the spatial heterogeneity of different materials at the larger scale might lead to dynamic effects in transient experiments. We used numerical simulations for heterogeneous parameter fields to evaluate in how far the outflow dynamics in heterogeneous fields can be reproduced by static hydraulic properties determined in simulated ideal experiments.

2. Multi-step-outflow experiments

2.1. Experimental setup

Classical multi-step-outflow (MSO) and two-step-outflow (TSO) experiments were performed. The sample (16.2 cm diameter, 10 cm height) was placed on a porous plate to control the water potential at the lower boundary. We used a 0.5 mM $CaCl_2$ solution. The dynamics of water outflow was measured with high temporal resolution. Additionally, a tensiometer was installed 8 cm above the lower boundary to measure the dynamics of the water potential during the experiments. The sample was an artificially packed heterogeneous sand build up by a random arrangement of cubes of three different sands with mean grain diameters of 0.125, 0.5, and 0.9 mm, respectively. The sample was constructed in five layers using a metall grid with grid cells of $2 \times 2 \times 2\ \mathrm{cm}^3$ which were filled by the different sands according to a random pattern. At the boundaries of the samples the cubes are truncated. To compare multi-step and two-step outflow experiments the detailed structure is not of primary importance, however, it should be noted that the coarse sand was continuous throughout the sample such that all coarse sand has a continuous connection to air. This is true if the cubes are considered to be connected not only through common faces but also through edges. This sample was also designed to investigate the possibility of downscaling hydraulic parameters which will be reported in a forthcoming paper.

To compare MSO and TSO experiments for a specific sample the different experiments have to be performed in a series. For a quantitative comparison of the results it is