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Quantifying soil heterogeneity from solute dispersion experiments

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ABSTRACT

The complicated morphology of the pore space of sandy/clayey/silty soils is characterized by multi-scale heterogeneities. The quantification of soil heterogeneity is a difficult task associated with a high uncertainty. For this purpose, miscible displacement experiments were performed on undisturbed and heterogeneous soils. The solute concentration averaged over various cross-sections was determined by monitoring the electrical conductivity with pairs of rod electrodes. The solute concentration breakthrough curves were measured on three cross-sections of two undisturbed soil columns at various flow rates. The datasets of all experiments were fitted successfully using a multi-region model in which the heterogeneous medium is regarded as a system of parallel homogeneous regions quantified by two parameters: (i) the longitudinal dispersivity a_L, a measure of the macro-heterogeneity, which reflects the intensity of preferential flow paths; (ii) the standard deviation σ_{k^*}, of the region permeability distribution, a measure of the micro-heterogeneity related to variations of the effective pore radii. Macroscopic simulations show that the estimated region log-permeability distribution shifts to lower values and its standard deviation increases compared to the actual permeability distribution.

1. Introduction

The contamination of soil and groundwater by liquid pollutants includes a wide variety of multiphase transport processes (e.g. gravity flow, dissolution, sorption, dispersion, etc.) occurring in a multi-scale heterogeneous pore space. Regarding solute dispersion in soils, numerous approaches have been developed and tested for the interpretation of soil column and field experiments on heterogeneous media. Nevertheless, there is a lack of simple and fast methods of analysis that will enable the practitioner to (a) estimate the effective transport coefficients introduced as input parameters into macroscopic simulators (e.g. dispersivity), and (b) quantify the heterogeneity of the porous medium.

Pore network simulations (Bruderer and Bernabe, 2001) revealed that as the heterogeneity of the pore structure increases, the longitudinal dispersion coefficient D_L also increases, and its dependence on Peclet number D_L (*Pe*) fits to a power law tending from 2 (Taylor dispersion) to unity (macrodispersion). Lab-scale experiments performed on porous media exhibiting high contrast of permeabilities have revealed late breakthrough of solute and tailing (Bajracharya and Barry, 1997; Drazer et al., 1999; Zinn et al., 2004). However, the tail of solute concentration breakthrough curves is unable to be reproduced by the conventional advection–dispersion equation using a mean pore velocity and a dispersion coefficient. In this direction, two-region models, subdividing the pore space into a mobile and an immobile zone have widely been used to interpret the experimental results and estimate all pertinent transport parameters (Gwo et al., 1998; Drazer et al., 1999). Alternatively, the two-region model has been used to reproduce the solute breakthrough curves of mildly heterogeneous porous media by estimating not only the dispersion coefficients, but also the pore velocity at each region, the difference of which is proportional to the thickness of the dispersion front (Aggelopoulos and Tsakiroglou, 2007).

Strong variations of permeability in heterogeneous soils are associated with non-uniformities in the fluid velocities. Most of the flow is transferred along a few tortuous channels so that solute molecules move rapidly, following the streamlines of these channels. This phenomenon is commonly defined as "preferential flow" (Rosqvist and Destouni, 2000; Hendrickx and Flury, 2001; Gerke, 2006). Much attention has been paid on the development of models in order to interpret solute dispersion in dual porosity media where the preferential flow through fractures and macropores is dominant (Vogel et al., 2000; Kim et al., 2005). Attempting to interpret soil column tracer tests, various multi-domain models have been developed to quantify the effects of the broad distribution of pore sizes, and pore water velocities on solute dispersion (Gwo et al., 1995; Durner and Flühler, 1996). An analytical model based on a continuous distribution of local flow velocities indicated that the macroscopic dispersion coefficient increases with the variance of the microscopic flow velocity and changes linearly with the average flow velocity (Skopp and Gardner, 1992).

Visualization techniques have been used to examine preferential flow in undisturbed soils using either computed tomography (CT)

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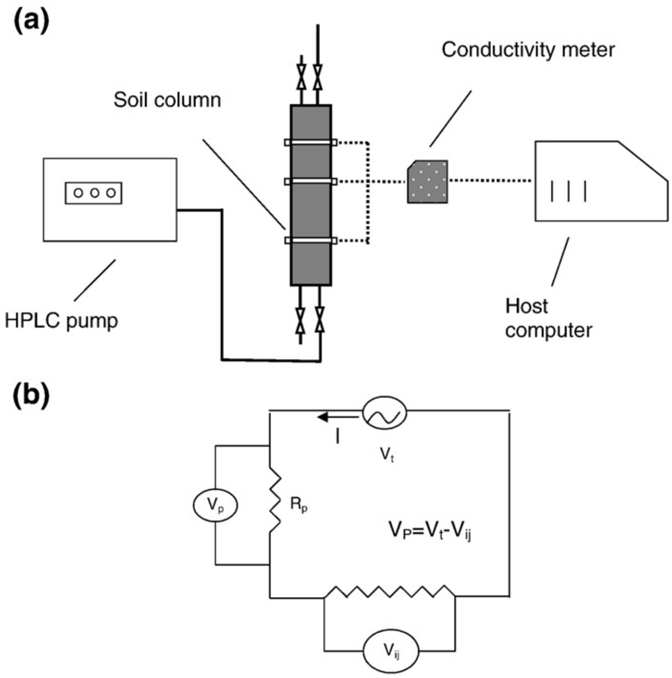

Fig. 1. (a) Experimental setup of miscible displacement experiments. (b) Schematic diagram of conductivity meter.

images or iodine-starch staining (Heijs et al., 1996; Hangen et al., 2004). Bruderer-Weng et al. (2004) studied flow channeling in heterogeneous pore networks and its implications on dispersion. They observed that flow channeling results in an increase of the asymptotic dispersion coefficient and strengthens when heterogeneity is enhanced. Dispersion experiments performed on undisturbed aquatic sediments (Roychoudhury, 2001) revealed that very broad pore size distributions result in non-ideal flow conditions characterized by tails of the solute concentration breakthrough curves.

In general, there is an ambiguity concerning the length-scale effect on the dispersion coefficient of heterogeneous soils. Experiments in soil columns indicated that the relationship between the dispersion coefficient and the length of porous medium fits to an exponential function for the homogeneous soils and a power law function for the heterogeneous soils (Huang et al., 2006). A number of experimental and numerical studies were conducted to clarify whether the equations describing fluid transport at local scales are also applicable to larger scales (Fernandez-Garcia et al., 2002). It was found that the apparent dispersivity appeared to be higher in directions of high hydraulic conductivity.

The goal of the present work is to develop a simple, fast and robust method for the simultaneous estimation of the longitudinal dispersivity and quantification of the heterogeneity of undisturbed soils. To this scope, an apparatus is constructed where the solute concentration, averaged over various cross-sections, is detected by measuring the transient response of the electrical resistance between horizontal rod electrodes that have properly been assembled in the soil holder. A two-parameter multi-region model is formulated to describe the transient response of the solute concentration at any axial position along the soil column. The heterogeneity of the soil is quantified by the standard deviation of the region permeability distribution. The dispersivity and heterogeneity of two undisturbed sandy/clayey/silty soils are estimated at various flow velocities with inverse modeling of the transient solute concentration breakthrough curves, measured at three cross-sections. The applicability of the multi-region model is evaluated with inverse modeling of the solute concentration breakthrough curves calculated with simulations on 2-D layered and periodic porous media.

2. Materials and methods

2.1. Experimental setup

An experimental apparatus was constructed to measure the electrical conductance of undisturbed soils during miscible displacement experiments. The apparatus consists of a sample holder (Fig. 1a), an in-house constructed multi-point conductivity meter (Fig. 1b), a HPLC pump and a data acquisition system (Fig. 1a).

A core holder was constructed to perform flow tests on undisturbed soil columns (Figs. 2, 3). The core holder was equipped with two end electrodes and five pairs of intermediate rod electrodes that allow the measurement of the electrical resistivity over various cross-sections of the soil column (Fig. 3a). The diameter of the rod electrodes was d=0.3 cm and their ends inside the soil were placed 1 cm apart. Their dimensions were much smaller than those of the column so that any potential disturbance on the flow field might be neglected. Each undisturbed soil sample was transferred carefully from the sampler into a rubber sleeve (Fig. 3a). Rod electrodes were inserted inside the soil by drilling the rubber sleeve and sealing the holes with plastic taps and glue (Fig. 3a). The total length of the soil column was L=32.7 cm and its diameter D=4.75 cm (Figs. 2a and 3a). The entire system (sleeve and soil column) was closed tightly with end electrodes and plastic caps (Fig. 2b) and placed inside a metallic holder of adjustable length (Fig. 3b). During the experiments, dry air was injected via a hole into the holder and an overburden pressure was exerted on the sleeve to avoid soil expansion and fluid leakages. An additional air-tighten port of the holder served for the connection of the cables of electrodes with conductivity meter without disturbing the gas overburden pressure (Fig. 3b).

A multi-point conductivity meter (Fig. 1b) was constructed for the on-line measurement of the electrical resistance between pairs of rod electrodes at various axial positions along the soil column (Fig. 3a). The AC electric current emitted by a power source (V_t=1 V) is determined by measuring the voltage across a standard resistance that is equal to 1 kΩ and is connected in series with the soil column. The average conductance over each cross-section is determined by measuring the corresponding voltages, V_{ij}, between rod electrodes (Fig. 1b). All measurements were conducted at a constant frequency of 500 Hz, but this parameter can be adjusted by the operator before initiating the experiment. The smallest voltage measured was 4 mV. However, the resolution of the technique (the smallest concentration difference that can be detected) relates to the smallest electrical resistance detected and depends on the soil type (formation factor) and solute concentration range used.

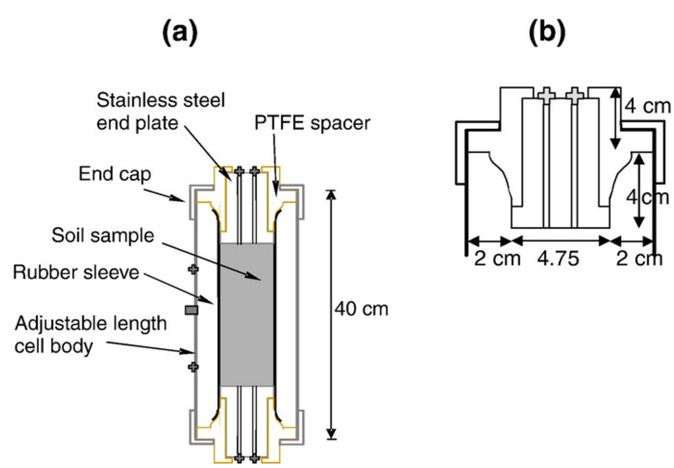

Fig. 2. (a) Schematic diagram of the resistivity cell of undisturbed soils. (b) Upper part of soil column holder.