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Advances in Water Resources 31 (2008) 1253–1268

Advances in Water Resources

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From the pore scale to the lab scale: 3-D lab experiment and numerical simulation of drainage in heterogeneous porous media

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Received 15 March 2007; received in revised form 14 September 2007; accepted 19 September 2007
Available online 4 October 2007

Abstract

A well-controlled 3-D experiment with pre-defined block heterogeneities is conducted, where neutron tomography is used to map 3-D water distribution after two successive drainage steps. The material and hydraulic properties of the two sands are first measured in the laboratory with multistep outflow experiments. Additionally, the pore structure of the sands is acquired by means of image analysis of synchrotron tomography data and the structure is used for pore-scale simulation of one- and two-phase flow with Lattice-Boltzmann methods. This gives us another set of material and hydraulic parameters of the sands. The two sets of hydraulic properties (from the lab scale and from the pore scale) are then used in numerical simulations of the 3-D experiment.

The paper discusses critical aspects and benchmarks for experimental measurements of 3-D water distribution in heterogeneous porous media. Additionally, we discuss possibilities as well as difficulties and limitations in the determination of hydraulic properties of materials using two conceptually different approaches (pore scale and lab scale). We then test with the numerical simulations how good can predictions on flow and water content in structured media be when using these state-of-the-art methods for the determination of hydraulic properties. Based on the numerical simulations, we discuss which parameters are more difficult to predict and which of the two approaches (lab scale or pore scale) enables better predictions.

Keywords: 3-D experiment; Neutron tomography; Heterogeneity; Two-phase flow; Numerical simulation; Pore scale; Lab scale; Lattice-Boltzmann

1. Introduction

Multiphase flow occurs in various natural or technical systems, for example, during infiltration of water in the unsaturated zone. The processes that take place in such systems are highly complex. Commonly, hydraulic properties are used to describe the interaction between the fluid phases and the solid phase in the heterogeneous subsurface. Numerical simulations are increasingly employed to predict two-phase flow in heterogeneous media. In order to make correct predictions, one needs to have accurate information about the hydraulic properties. This is, in general,

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doi:10.1016/j.advwatres.2007.09.006

very difficult when dealing with field applications. Even if properties of samples are known, the complexity of real soils makes it practically very difficult to precisely represent soil patterns in field applications. In practice, structure has to be estimated, while hydraulic properties from local measurements are used.

1.1. Relevant work

Several multidimensional numerical models which can simulate multiphase flow processes based on different approaches [1,21,37] have been developed to make predictions of lab scale or field scale applications. Most of the numerical studies considering heterogeneities have been carried out for 1-D and 2-D problems [30,16,13,18,15]. Some 3-D simulations have also been applied to predict multiphase flow in case studies or field applications [40,22]. However, it is very difficult to validate results from 3-D simulations due to the complexity of the problems under investigation, the scarcity of good 3-D laboratory or field data and the lack of knowledge related to the hydraulic properties. In addition, it is not clear how good predictions can be even if the most accurate methods are used for the determination of hydraulic properties.

The classical approach to determine hydraulic properties of porous media is to carry out multistep outflow experiments, where a porous medium sample is saturated with water and then drained by decreasing the boundary pressure stepwise (i.e. [35]). Inverse models are then applied to determine the hydraulic properties from the measured outflow curve (i.e. [41]).

Another approach for the determination of hydraulic properties of porous media is to derive them from knowledge about the pore-scale structure. There are several publications on the determination of pore-scale structure of porous media. For example, Lehmann et al. [33] have scanned sand material with a synchrotron light source to determine packing effects on the porosity at the interface between different sand types. Predictions of hydraulic properties have been done by means of pore network models. Bryant and Blunt [9] and Juanes and Patzek [26] have predicted relative permeabilities in two- and three-phase flow systems while Vogel and Roth [50] used topological parameters similar to those of natural soil samples in order to determine soil hydraulic functions. Pore network models have also been used to model multiphase flow in porous media [5] and their predictions have been compared to fluid distributions measured in small samples using synchrotron tomography [10]. It is also possible to determine hydraulic properties of porous media using the exact geometry of the pore space taken from scanned sand samples and by means of pore-scale flow simulations utilizing Lattice-Boltzmann methods [2,34,8,45,39,51,3].

Various experimental studies can be found in the literature, both for NAPL–water and air–water systems, that address the problem of flow in heterogeneous media and where the movement of the fluids is monitored. Experiments for the investigation of two-phase flow in 2-D heterogeneous media were carried out i.e. by Kueper et al. [31], Wildenschild and Jensen [52], and Ursino et al. [47]. Relatively few 3-D experiments have been carried out using X-ray computed tomography (CT) to investigate water distribution in soils [23,20]. Recently, Culligan et al. [11,12] have used CT techniques to measure interfacial areas in 3-D glass bead structures. A quite new method for mapping in 3-D is neutron tomography: a first application was done by Solymar et al. [44], while Masschaele et al. [36] used neutron tomography to qualitatively investigate dynamic processes in limestone and sandstone. In some cases, the monitored distribution of fluids in 2-D or 3-D heterogeneous media has been compared to numerical simulations, i.e. [48]. However, agreement between measurement and prediction could be found only in a qualitative way. Laboratory experiments commonly involve pre-defined heterogeneities and therefore provide the advantage that the structure is known. However, an uncertainty in such studies remains from the strong influence of the hydraulic properties used as input in the numerical simulations.

1.2. Objectives

To summarize, there are state-of-the-art methods to map 3-D fluid distribution in heterogeneous porous media, numerical tools for the simulation of 3-D two-phase flow in heterogeneous media, fairly accurate techniques to determine hydraulic properties of sands in the lab and advanced modelling approaches for the computation of hydraulic properties from the pore scale. Aim of this paper is to provide knowledge related to predictions of two-phase flow in heterogeneous media using hydraulic properties measured with high end methods. The following working steps are presented (see also Fig. 1):

- The hydraulic properties of two materials (porosity, permeability and capillary pressure–saturation relationship) were determined in the laboratory by means of multistep outflow experiments (Fig. 1b).
- The hydraulic properties of the same materials were also determined with advanced image analysis of scanned pore structures and pore-scale numerical simulations utilizing Lattice-Boltzmann methods (Fig. 1c).
- A well-controlled 3-D drainage experiment was conducted using a pre-defined heterogeneous arrangement of the two materials (Fig. 1d). We measured
  - the equilibrium times for two successive drainage steps,
  - the 3-D water distribution in the heterogeneous column at quasi steady-state.
- Numerical simulations of the 3-D experiment were carried out using the hydraulic properties determined at the lab scale (Fig. 1e).
- Numerical simulations of the 3-D experiment were also performed using as input the hydraulic properties determined at the pore scale (Fig. 1f).