Experimental investigation of preferential flow in a near-saturated intact soil sample

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Abstract

Hydraulic conductivity in an intact sample of coarse sandy loam from the Cambisol series containing a naturally developed, vertically connected macropore was investigated during a recurrent ponding infiltration (RPI) experiment performed over a period of 30 hours, in combination with neutron tomography imaging. The RPI experiment consisted of two consecutive ponded infiltration runs, each followed by free gravitational draining of the sample. Three-dimensional neutron tomography (NT) imaging of the dry sample was acquired before the infiltration began. The dynamics of the advancement of the wetting front was investigated using a sequence of neutron radiography (NR) images. Analysis of these images showed that the water front moved preferentially through the macropore at an approximate speed of 2 mm/s, significantly faster than the 0.3 mm/s wetting advancement in the surrounding soil matrix. After outflow started temporal changes in the local water content distribution were evaluated quantitatively by subtracting the NT image of the dry sample from the particular tomography images generated during infiltration runs. The neutron tomography data quantitatively showed the transfer of air from the soil matrix to the macropore. Accumulation of air bubbles in the macropore then affected the hydraulic conductivity of the sample reducing it to 50% of the initial value.

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1. Introduction

In heterogeneous and highly structured soils, and in soils that contain cracks, fissures or macropores, water can move at a significantly higher velocity in these structures than in the soil matrix (Beven and Germann, 1982). Local pressure non-equilibriums are not considered in the governing flow equation (Richards’ equation). Various models of two-domain approaches have been introduced to simulate flow and transport in structured soils (Long et al., 1982; Arbogast et al., 1990; Jarvis et al., 1991), specifically the so-called dual-permeability approach. Two Richards’ equations are solved for two macroscopic flow domains (Gerke and van Genuchten, 1993; Vogel et al., 2010a). In the dual-permeability model each domain is represented by its own set of hydraulic properties and additional parameters characterize communication between the domains. The large number of parameters that must be determined represent the major limitation on wider use of dual permeability models. In addition, flow in preferential pathways at near-saturated conditions is also affected by the movement of air, a factor not normally taken into account in subsurface hydrology models. Previous experiments have shown that the air is trapped in the pores of natural soils (Faybishenko et al., 1995; Snehota et al., 2010) and packed samples (Geistlinger et al., 2014; Snehota et al., 2015) affecting flow of water.

The aim of the experiment presented here was 1) to monitor quantitatively the transfer of water from a fine soil matrix into preferential pathways during the redistribution of entrapped air and 2) to image the process of entrapped air dissolution. To fulfill these goals the experiments needed to be performed in higher resolution.

Nomenclature

| RPI | recurrent ponded infiltration |
| NR  | neutron radiography           |
| NT  | neutron tomography            |

2. Infiltration-outflow experiment

2.1. Sample preparation

Six undisturbed samples (see Fig 1a) were carefully collected from 40 cm depth at an experimental site near Korkusova Hut, Czech Republic. One sample with an apparent macropore was selected for the infiltration outflow experiment.

Fig. 1. (a) Undisturbed soil sample prepared for the infiltration outflow experiment; (b) example of scanning electron microscopy image of the soil under the study, black areas represent pores.
The soil type at the site is Dystric Cambisol with coarse sandy loam composition. Mass fractions of the particle size distribution were 7.2, 18.4, 21.3, 33.6, 13.4, and 6.1% for grain size categories <2 \( \mu m \), 2 to 20 \( \mu m \), 20 to 200 \( \mu m \), 0.2 to 2 mm, 2 to 12.5 mm, and >12.5 mm, respectively. The mass content of Fe in soil at the site is relatively high at 1.35 %, typical organic matter content is 2.98 % (Hall et al., 1997). The broad pore size distribution and complexity of the pore geometry is documented by the Scanning Electron Microscopy image presented in Fig. 1b.

The soil sample was initially taken in a steel tube with internal diameter of 34 mm by gradually pushing the tube in the soil. The tube was transported to the laboratory and the sample’s surface was exposed to the air. The air-dry soil was then transferred from the steel tube to a quartz glass tube of the same internal diameter. The outer surface of the soil column was sealed with a paste made of fine particles of the same soil mixed with heavy water to prevent bypass flow during the experiment. The length of the soil column in the glass tube was 87 mm. The sample was then saturated with heavy water. The glass tube was inserted into an aluminum funnel, supported by an aluminum perforated plate which allowed free water and air flow through the bottom of the sample.

2.2. Infiltration outflow experiment

The experiment was conducted at the NEUtron Transmission RAdiography (NEUTRA) beam line of the Swiss Neutron Spallation Source (SINQ), at the Paul Scherrer Institute (PSI) in Villigen, Switzerland (Lehmann et al., 2001). In principle, the experiment simulates the rapid infiltration of water that occurs in nature during high intensity rainfall events. We started the infiltration experiment by flooding the soil sample surface with heavy water. The depth of water atop the sample was maintained at a constant level.

Water infiltrated into the sample, the wetting front progressed to the bottom of the sample and the soil gradually became saturated. Water seeped through the perforated plate, dripped into the aluminum funnel. Outflow was continuously collected in the funnel and transferred by a constantly running peristaltic pump to a bottle placed on a digital balance. The outflow fluxes were thus measured continuously during the experiment.

The infiltration was maintained for 8.5 hours, the sample was then allowed to drain by gravity and equilibrate for 6.4 hours. The second infiltration run was then started and maintained for 7.1 hours followed again by gravity drainage.

3. Neutron imaging

3.1. Neutron radiography

Neutron radiography (NR) was used to monitor the time-resolved progress of the rapid transient infiltration in our experiment. The detector used was a 100 \( \mu m \) thick LiF/ZnS scintillator screen photographed by a cooled charge coupled device (CCD) camera. The image exposure time was 8 s. The radiography images were acquired in 16 s interval. The image matrix size was 1024 \( \times \) 1024 pixels and nominal pixel size was 0.1 \( \times \) 0.1 mm\(^2\).

The raw images were corrected for beam and detector spatial and temporal changes (Kaestner et al., 2008) and corrected for beam hardening effects by the modified method of Kang et al. (2013). The details of the radiography procedure are given by Sacha et al. (2015). The horizontal thickness of the infiltrated heavy water detected in each pixel was calculated relatively with respect to the initial saturation, similar to the method used by Carminati et al. (2008). The equation used for these calculations is:

\[
\ln \left( \frac{I_{\text{INIT}}}{I_{\text{WET}}} \right) = \frac{d_{D,O}}{\Sigma_{D,O}}
\]  

(1)
where \( \Sigma_{D,0} \) is the linear attenuation coefficient of heavy water and \( d_{D,0} \) is the thickness of the water. \( I_{\text{INIT}} \) and \( I_{\text{WET}} \) are corrected image pixel values measured after a beam passed through the sample before the experiment and during infiltration.

3.2. Neutron tomography

The images generated were utilized to produce 3D images of water distribution within the sample at selected “steady state stages” of the experiment. For each tomogram 201 radiographs were utilized. A 3D image was then generated using the MUHREC software package (Kaestner, 2011).

4. Results and Discussions

The time lapse neutron radiography corrected image taken before the infiltration is shown in Fig. 2a. The maps of water thickness constructed from the individual radiography images (see selected images in Fig. 2b) showed that the vertically connected macropore quickly filled with water once ponding occurred at the top of the sample. The wetting front in the macropore moved at a rate of approximately 2 mm/sec. Water in the rest of the sample (finer soil matrix) infiltrated at a rate of approximately 0.3 mm/sec. Lateral flow from the macropore to the surrounding soil is also evident in Fig. 2b. The dataset clearly illustrates preferential macropore flow.

Fig. 2. (a) Neutron radiography image corrected for the detector and beam inhomogeneity of the sample before the infiltration started; (b) Time-lapse series of images expressed as maps of water thickness, after corrections and subtracting the first image.

Fig. 3. Comparison of water volume actually added to the sample surface by peristaltic pump and volume of water derived from the neutron radiography images.
The volume of water in the sample calculated from the maps of water thickness was in good agreement with amount of water actually applied at the top of the sample (see Fig. 3). Note that water volume calculation included the ponding water. Fig. 4 shows that volumetric flux measured at the outflow from the sample rose sharply soon after first outflow appeared to 0.48 cm/h. Then, during the stage of the experiment in which steady state flow would be expected, the outflow rates gradually dropped to a value of 0.2 cm/h. This is consistent with results of previous experiments conducted on the same soil.

![Graph showing volumetric flux](image1)

Fig. 4. Plot of the volumetric flux of the outflow from the sample (blue line) with indication of times of neutron tomography imaging (gray line)

Detailed analysis of the neutron tomography image of the dry sample suggests that the macropore was formed by root growth (Fig. 5). The decayed root is still visible in the image. The macropore was mostly cylindrical and connected the top of the sample to the bottom. Other structures found in the tomography image included narrow fractures that were apparently created during sample drying. This happened during the initial drying of the sample in the steel tube. Soil apparently adhered to the tube wall, as the steel corroded, and then cracked when soil contracted at air dry water contents. Stainless steel tubes should be used instead of regular carbon steel in the future, to allow detachment of soil from the tube walls during initial drying.

![Image showing neutron tomography](image2)

Fig. 5. Example of vertical slices of five selected tomograms, that shows filling and draining of the macropore and air trapping. Darker gray levels show lower attenuation (black color represents air) coefficient while brighter areas represent areas of high attenuation (e.g. heavy water in the macropore). The newly developed air bubble is visible in the enlarged part of the vertical slices of tomogram T05.
A series of 22 neutron tomography images was acquired before and during the two infiltration runs. Neutron tomography images T03 through T05 showed that air bubbles gradually developed in the macropore. According to the hypothesis suggested by Snehota et al. (2010) the air that formed these bubbles came from the fine pores of the surrounding soil matrix in which it was trapped at the beginning of the initial wetting. Air was gradually replaced by water attracted into small pores by strong capillary forces. Redistributed into larger air bubbles then increasingly blocked the flow through the macropore and decreased effectively the flow rate. When the sample was gravitationally drained (see Fig. 5, tomography image T12), water left the macropore, which filled with air. When the second infiltration run started and water content of the sample reached equilibrium, many large bubbles stayed trapped in the macropore. Flow rate in this case remained at an average rate of 0.18 cm/h.

4. Conclusions

Recurrent infiltration outflow experiment monitored by neutron imaging showed that entrapped air redistribution occurred in heterogeneous porous media and had impact on the “steady” state flow rate which is proportional to the saturated hydraulic conductivity and for a given sample should be constant. Steady state flow rate through the sample that is directly related to the hydraulic conductivity of soil was affected by the amount of entrapped air and the most importantly by its spatial distribution.

The complementary investigation presented by Sacha et al. (2015) confirmed that the flow rate changes observed here take place also in case of rigid artificially prepared heterogeneous composed sample.

The quantitative data of water distribution changes during a recurrent ponding infiltration-outflow experiment, are ready to be used to enhance i) the simulation model based on the dual permeability approach (Vogel et al., 2010b) and ii) the model based on the two phase flow approach (Fucik et al., 2010), the both are being developed at the Czech Technical University in Prague.

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