REDISTRIBUTION OF CAPILLARY TRAPPED GAS PHASE IN POROUS MEDIUM: NEUTRON IMAGING STUDY

Michal Sněhota*[1,2], Jan Šácha†[1,2] & Jan Hovind‡[3]

[1]Czech Technical University in Prague, Civil Engineering, Department of Irrigation, Drainage and Landscape Engineering, Prague 6, Czech Republic
[2]Czech Technical University in Prague, University Centre for Energy Efficient Buildings, Architecture and Interaction of Buildings with Environment, Bustehrad, Czech Republic
[3]Paul Scherrer Institut, Laboratory for Neutron Scattering and Imaging (LNS), Research with Neutrons and Muons,Villigen PSI, Switzerland

Keywords: neutron imaging, radiography, tomography, non-wetting phase, capillary trapping, entrapped air

Summary: Capillary trapping of non-wetting phase prevents full saturation of the porous media including soil. Neutron tomography was utilized to quantitatively measure the mass transfer of air from regions fine-grained material to coarse-grained material in quasi-saturated porous media. The effect of capillary trapped gas on water flow was evaluated.

1. INTRODUCTION

Infiltration is the key hydrological process that affects a generation of runoff, flood formation, water erosion, and leaching of contaminants through a soil layer. These processes are often most intensive in nearly saturated soils. It was shown that soils rarely reach full water saturation, thus residual air content resides in pores [1]. The consequences of partial water saturation are the increased gas storage and reduced hydraulic conductivity [2]. The extent of the impact of trapped air on soil water processes depends on the amount of entrapped air, and even more, on its spatial distribution [3] within the pore space. Recent experiments showed that neutron tomography has sufficient sensitivity to quantitatively detect small changes of water content, and thus the changes of trapped air content in dual porosity material [4]. The aim of this study was to assess quantitatively the air trapping and subsequent redistribution in the dual-permeability material during water flow as well as during situation at which water in the nearly saturated soil does not flow.

2. EXPERIMENTAL METHOD

Redistribution of trapped gas was quantitatively studied by three-dimensional (3D) neutron imaging in series of experiments conducted on a sample composed of fine porous ceramic (Porous Ceramic, ½ bar, HF, SoilMoisture Equipment Corp., Santa Barbara, CA), and coarse sand (0.1-0.8 mm grain size). The redistribution of water was studied under no-flow and steady state flow conditions. To build the sample, the cylinder of the porous ceramic was shaped into the axisymmetric body of variable radius. The ceramics were placed in the quartz glass cylinder and the space between ceramics and sample container was gradually filled with dry sand. The resulting sample contained two materials of contrasting hydraulic properties that can be viewed as domains of fast and slow flow. Both domains were interconnected from the top to the bottom of the sample. The inner diameter of the sample was 29.3 mm and the height was 30.7 mm.
Two narrow air pressure sensors were installed into the sample through the bottom to monitor residual air pressure in two locations. One pressure sensor was placed into the sand, while the second one was installed in the ceramics. A series of ponded infiltration experiments was conducted on a sample by delivering heavy water (a mixture formed by 10 % H_2O and 90 % D_2O) with a peristaltic pump to the top of the sample while maintaining a constant water level. Water infiltrated under slightly positive water pressure, the condition referred as ponding. The water was allowed to flow freely by gravity through the perforated disc at the bottom of the sample. Four continuous and three intermittent infiltration runs were conducted on the sample with different initial water contents. The initial condition was set by tension drainage and using a flow of dry air.

* e-mail: michal.snehota@fsv.cvut.cz
† e-mail: jan.sacha.1@fsv.cvut.cz
‡ e-mail: jan.hovind@psi.ch

The neutron imaging was conducted at Neutron Radiography (NEUTRA) beam line of the Swiss Neutron Spallation Source (SINQ) at the Paul Scherrer Institute (PSI) in Villigen, Switzerland [5]. For the neutron tomography imaging, the sample was rotated in 400 angular steps covering the total angle range of 360°. The detector was a 100 μm thick LiF/ZnS scintillator screen photographed by a cooled CCD camera. The image exposure time was 5 s. The field of view of the detector was 69.75 × 64.64 mm, the image matrix size was 750 × 695 pixels, which resulted in a nominal pixel size of 0.093 × 0.093 mm2. The reconstruction was done using the MUHREC software package [6]. A total number of 69 tomography images were taken for this study. Images that represented the three-dimensional spatiotemporal distribution of air and water in the sample were calculated with use of images of fully saturated and dry sample [7].

3. RESULTS

Based on the robust experience of visualization of the flow within heterogeneous samples, it seems that due to the huge local (microscopic) pressure gradients between contrasting pore radii the portion of faster flowing water becomes attracted into small pores of high capillary pressure. The process depends on the initial distribution of entrapped air which has to be considered as random in dependence on the history and circumstances of wetting/drying.

The rate of the redistribution was significantly higher in the case of steady state flow condition in comparison to no-flow conditions. Figure 1 also demonstrates that residual air accumulated preferentially on the interfaces between coarse sand and fine ceramics. The transfer from fine to large pores leads to reduced hydraulic conductivity of the sample.

References

[1] Faybishenko, B. A. (1995), Hydraulic behavior of quasi-saturated soils in the presence of entrapped air - Laboratory experiments, Water Resources Research, 31(10), 2421-2435.

[2] Votrubova, J., M. Cislerova, M. H. G. Amin, and L. D. Hall (2003), Recurrent ponded infiltration into structured soil: A magnetic resonance imaging study, Water Resources Research, 39(12).

[3] Dohnal, M., V. Jelinkova, M. Snehota, J. Dusek, and J. Brezina (2013), Tree-Dimensional Numerical Analysis of Water Flow Affected by Entrapped Air: Application of Noninvasive Imaging Techniques, Vadose Zone Journal, 12(1).

[4] Snehota, M., V. Jelinkova, M. Sobotkova, J. Sacha, P. Vontobel, and J. Hovind (2015), Water and entrapped air redistribution in heterogeneous sand sample: Quantitative neutron imaging of the process, Water Resources Research, 51(2), 1359-1371, doi: 10.1002/2014wr015432

[5] Lehmann, E. H., P. Vontobel, and L. Wiezel (2001), Properties of the radiography facility NEUTRA at SINQ and its potential for use as European reference facility, Nondestructive Test. Eval., 16(2–6), 191–202, Springer Science1Bussines Media, LLC. doi:10.1080/10589750108953075.

[6] Kaestner, A. P. (2011), MuhRec - A new tomography reconstructor, Nuclear Instruments & Methods in Physics Research Section a - Accelerators Spectrometers Detectors and Associated Equipment, 651(1), 156-160, doi: 10.1016/j.nima.2011.01.129

[7] Sacha, J., Snehota M., Hovind, J., (2016), A quantitative evaluation of the water distribution in a soil sample using neutron imaging [online]. Acta Polytechnica. 2016, 56s. 388-394. doi: https://doi.org/10.14311/AP.2016.56.0388

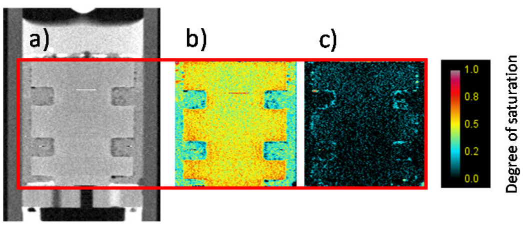

Figure 1: (a) Vertical slice of the neutron tomography image during infiltration-outflow experiment. a) reconstructed tomography image, b) water content and c) air content.