Laboratory visualization of two-phase flow in a natural fracture by neutron tomography

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A b s t r a c t: Due to their weak interaction with matter, thermal neutrons are highly penetrating and can be used as a non-destructive probe for complex structures. As water has a high macroscopic cross section, neutron radiography is suitable to investigate moisture content of rock samples. We use neutron tomography to visualize imbibition and drainage in a core containing a fault-gouge filled fracture. The experiments show that air drainage is very irregularly distributed, supporting that air flows through preferential paths. During capillary imbibition the wet front rises rapidly. After a few minutes it assumes an almost steady-state profile and then a slow increase of moisture content in the already wet regions is observed. We suggest that water first fills a well-connected porosity then it is slowly sucked into a poorly connected porosity.

INTRODUCTION

Heterogeneity of fracture properties may yield unevenly distributed multiphase flow and transport. The behaviour of the system strongly depends on the pore-volume distribution and the nature of the heterogeneities (Lunati et al., 2003; Lunati, 2003). In case of a complicated structure such as a shear zone in crustal rocks, it is desirable to directly observe the water transport phenomena and assess whether the flow takes place in a few preferential paths or is evenly distributed over the whole fracture.

Non-destructive investigation of two-phase flow in a granite core was performed by Chen and Kinzelbach (2002) by nuclear magnetic resonance (NMR). However, due to the paramagnetic properties of granite, only low-intensity magnetic fields can be applied, which do not allow high resolution: only an overall pore-size distribution can be measured reliably. A technique that allows better spatial distribution is neutron radiography. This technology was used in the past to investigate the moisture distribution in different materials (Lehmann and Vontobel, 2000; Pleinert et al., 1998; Pleinert and Degueldre, 1995; Degueldre et al., 1996). We use neutron radiography to investigate two-phase flow in a core containing a fault-gouge filled fracture. We study both capillary imbibition in the dry sample and drainage by air injection in the saturated sample (see also Lunati, 2003).

NEUTRON RADIOGRAPHY: THEORETICAL BACKGROUND AND TECHNOLOGY

The transmission behaviour of a neutron beam can be described by the simple exponential attenuation law, i.e. \( I = I_0 \exp(-\Sigma d) \), where \( I \) is the intensity of the transmitted beam \([\text{n/cm}^2\text{s}]\), \( I_0 \) the intensity of the incident beam \([\text{n/cm}^2\text{s}]\), \( d \) the thickness of the sample \([\text{cm}]\), and \( \Sigma \) the macroscopic cross section \([\text{cm}^{-1}]\). (Deviations have to be expected and taken into account for thick samples or strongly interacting material.) Since different materials have a different macroscopic cross section, by comparison between the incident and transmitted beams, we can obtain information about the sample composition. Due to the high macroscopic cross section of water, neutron radiography represents a powerful tool to investigate moisture distributions.

Our experiment is performed at the NEUTRA radiography facility of the Paul Scherrer Institute in Villigen (AG, Switzerland – http://neutra.web.psi.ch/). The incident beam of thermal neutrons is produced by the spallation source SINQ; it has a neutron flux of \( 7.7 \times 10^8 \text{n/cm}^2\text{s} \) and a collimation ratio of 350. The transmitted beam is recorded by a Peltier cooled CCD camera as a 2D projection of the object with a spatial resolution of 115 \( \times \) 115 \( \mu \text{m} \) determined by the camera lens used. The sample is fixed on a rotating table, which permits a rotation in small angular steps over 180\(^\circ\) and allows the reconstruction of fully 3D information from the 2D projections by computed tomography (CT).

THE FRACTURE SAMPLE

The core was drilled in the Grimsel Granodiorite at the GAM experimental site in the Grimsel Underground Laboratory (BE, Switzerland). At the upper face four fractures are visible, which contain a non-cohesive fault gouge material. A preliminary x-ray CT investigation was performed in order to assess the internal structure of the core and choose a fracture for the experiments, which is well separated from the others. This allows performing the two-phase flow experiment in a single fracture. Then, the sample is sub-cored (diameter of about 80 mm) and an aluminium tube is molded to the sub-core, the two vertical boundaries of the selected fracture being previously sealed (at least partially) with mortar in order to prevent a significant secondary flow between Al-tube and granite. After drying at 40\(^\circ\)C for about two weeks, a layer of silicon is spread on the two faces of the sample except the area corresponding to the fracture that is selected for the experiment. This is intended to seal the other fractures, as well as the space between the Al-tube and the core, and make them impermeable to the flow.

Fig.1 Top-left corner: Dry-sample radiography, projection in the direction perpendicular to the flow. Top center to bottom-right corner: ratios of the radiography at different times after capillary imbibition started and the dry sample radiography (top-left corner). These ratios show the water content (black) in the core at times 32sec, 9min 53sec, 32min 39sec, 1h 5min 54sec and 2h 5min 12 sec after the the bottom of the sample was brought in contact with water.

EXPERIMENTAL PROCEDURE

Capillary imbibition

A first experiment is aimed of visualizing the capillary rise of water in the dry sample. By comparing the transmission of neutrons through the sample before and after imbibition, we obtain information on the water distribution. Due to the thickness of the core, a relatively long exposition time (around 40 sec) is needed in order to guarantee an adequate intensity of the transmitted beam and a satisfactory image resolution.
After acquisition of fully three-dimensional information by tomographic reconstruction, the bottom of the sample is brought in contact with water and capillary suction starts. We observe the wetting front displacement by 2D radiographies. Each image acquired at a certain time step is normalized by the radiography of the dry sample, such that differences from the dry state are highlighted and water distribution results (figure 1). The front rises rapidly and after a few minutes the water appears irregularly distributed. After that, an increase of moisture content in the already wet regions is observed. We suggest that this reflects non-negligible conductivity effects during unsteady imbibition: even if the height of the capillary rise is completely determined by capillarity, imbibition might be slower if conductivity is low. We also observed a tendency for water to accumulate at the boundaries. Despite of the effort made in order not to disturb the fracture, we cannot completely exclude that the boundaries are perturbed during the core processing.

From 2 hours on, only slight variations are observed and the sample can be considered in a quasi-steady state. After 3 hours a tomographic image of the imbibed sample is acquired and compared with the tomography of the dry sample. It can also be observed that water is not uniformly distributed and air bubbles (visible as white spots) are present. This is due to the nature of the capillary force that sucks water into the small pores, whereas large pores are filled by air.

Water displacement by air injection

After the capillary-rise experiment, the sample is dried at 40°C for over a month. Then the core is saturated under vacuum conditions with degassed water and flushed for over 30 hours. A tomographic image is acquired, which shows the 3D distribution of the water phase in the sample. A non-complete saturation of the fracture selected for the experiment is observed: a few air bubbles are still entrapped in the fracture. In contrast, the other fractures are partially filled with water, despite of the silicon layer aimed to make them impermeable to the flow. The large amount of water in the saturated core and the rapid air breakthrough prevent us from observing the displacement of the air front. Despite of the effort to saturate only one of the four fractures in the core, water penetrates all of them, which yields a strong attenuation of the neutron beams such that fully 3D information is needed to obtain the necessary resolution and provide a detailed description of the air pressure and pathway determination in crystalline rock by positron emission and neutron radiography, Earth Planet. Sci. Lett., 140 (1-4): 213-225 1996


Lunati, I., Conceptual Model of Single and Multiphase Flow in a Fracture, ETH Zurich, Ph.D. Thesis no. 15082, 2003
