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Research paper

Reconstruction of the water content at an interface between compacted bentonite blocks and fractured crystalline bedrock

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ABSTRACT

High-density sodium bentonite combines a low permeability with a swelling behavior, which constitute two important qualities for engineered barriers in geological disposal of spent nuclear fuel. For example, the KBS-3V method developed in Sweden and Finland is planned to include compacted bentonite as the buffer material to embed canisters containing the spent nuclear fuel packages in deposition holes in deep crystalline bedrock. The partially saturated bentonite buffer will then swell as it takes up groundwater from the surrounding rock. It is important to quantify the water content evolution of the installed buffer to correctly predict the development of the swelling pressure and the prevailing conditions (thermal, mechanical, chemical and biological). This study aimed at quantifying the water content profile at the surface of a cylindrical bentonite parcel retrieved after in situ wetting in fractured crystalline bedrock. We demonstrate the possibility of using regression-kriging to quantitatively include spatial information from high-resolution photographs of the retrieved bentonite parcel, where more water saturated areas appear as relatively dark shades, along with bentonite samples, where detailed measurements of water content were performed. The resulting reconstruction is both exact regarding local sample measurements and successful to reproduce features such as intersecting rock fracture traces, visible in the photographs. This level of detail is a key step to gain a deeper understanding of the hydraulic behavior of compacted bentonite barriers in sparsely fractured rock. An improved scanning procedure could further increase the accuracy by reducing errors introduced by the geometrical transformations needed to unfold and stitch the different photographs into a single gray scale map of the bentonite surface. The application of this technique could provide more insights to ongoing and planned experiments with unsaturated bentonite buffers.

1. Introduction

Sodium bentonite is a clay with a high content of montmorillonite which grants it a swelling behavior in presence of water (Börgesson, 1985; Bucher and Müller-Vonmoos, 1989; Norrish, 1954) . This property and its low permeability make it a natural choice to engineer groundwater barriers in applications such as geological disposal of radioactive waste (Nagra, 2002; Posiva Oy, 2010; SKB, 2010). For example, the planned design of a repository for spent nuclear fuel in Sweden, denoted as the KBS-3 V method, comprises excavations of deposition tunnels approximately 500 m below the ground surface in crystalline bedrock. Deposition holes would then be drilled in the tunnel floors, and the canisters containing spent nuclear fuel in each hole would be embedded using compacted bentonite blocks and pellets (SKB, 2010). Bentonite is also considered as backfilling material for the deposition tunnels (SKB, 2010). The general idea is to insert partially saturated bentonite which then seals the underground openings as it draws water from the rock around the deposition tunnels and holes, and swells. One uncertainty is the global wetting pattern and water uptake rate of the buffer blocks under different in situ conditions and how these are influenced by the local rock properties (e.g. deposition hole inflow, local fracture network geometry, transmissivity) (e.g. Dessirier et al., 2015; Åkesson et al., 2010). Understanding flow interactions between the rock matrix, rock fractures and bentonite is an important component of accurate predictive modeling of water and air flows in the subsurface repository and fractured rock system (Dessirier et al., 2014), with implications for inert and reactive transport (Cvetkovic and Frampton, 2010, 2012; Frampton and Cvetkovic, 2007a,b, 2009, 2011) beyond the local deposition holes.

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Recognition of this need to develop the understanding of the dynamics of in situ wetting of bentonite in natural rock cavities led to the Bentonite Rock Interaction Experiment (BRIE) (Fransson et al., 2016).

BRIE was set up to observe and document the early evolution of compacted bentonite blocks in situ under isothermal conditions. It was conducted in an underground tunnel approximately 415 m below ground at the Äspö Hard Rock Laboratory (HRL) in southeastern Sweden. The characterization phase aimed at quantifying inflows into the BRIE tunnel, exploratory boreholes and deposition holes as well as describing the water-bearing fractures or zones responsible for those inflows (Fransson et al., 2016). The wetting phase of the experiment took place in two deposition holes with radius R=15 cm and depths of 3.5 (Hole 17) and 3.0 m (Hole 18) from the tunnel floor. Instrumented bentonite blocks were put in place and left to saturate for 419 (Hole 17) and 518 days (Hole 18). After that, the rock surrounding the deposition holes and the bentonite parcels were extracted and transported to the laboratory for sampling and analysis (Fransson et al., 2016).

Dessirier et al. (2016) used the gathered characterization data to build alternative models of the BRIE site and experiment. The array of models in that study served as a basis for scenario analyses of factors that govern patterns and rates of bentonite wetting with objective to relate different factors measured prior to deposition, to the subsequent bentonite wetting. Those results suggested that in most cases, the wetting rate of the buffer as a whole was not as strongly related to the total open-hole inflow rates as to the distribution of inflow along the holes, which emphasized the importance of local scale heterogeneity in permeability, including the absence or presence of water bearing rock fractures, in the deposition hole vicinity. Furthermore, the results presented in Dessirier et al. (2016) indicate a bias of models using a homogeneous rock matrix and representing the local fractures as homogeneous plates towards a consistent overestimation of the bentonite wetting rate. It has indeed been shown that flow in rough fractures takes place in a few preferential pathways (Tsang and Neretnieks, 1998). The absence of this flow channeling effect could explain the overestimation produced by homogenized models. However, the available characterization data, i.e transmissivity of borehole intervals and fracture mapping of rock cores, does not provide direct information on the channels intersecting the deposition holes and how to parametrize them within the models.

This study focuses on the interpretation of BRIE data on bentonite wetting and high-resolution water content patterns at, and close to, the surface of the bentonite parcel, which then may reflect expected critical heterogeneities in water transfer from the rock to the bentonite. More specifically, we considered the bottom meter of the bentonite parcel retrieved from one of the boreholes: BRIE Hole 18. After the surrounding rock had been prepared for extraction by stitch-drilling all around the deposition hole, the bentonite parcel could be extracted from the tunnel floor by pulling it in one piece, without significant damage to the bentonite surface. The retrieved bentonite parcel was then carefully wrapped in plastic for transport to the laboratory. Photographs of the surface of the bentonite were taken in the laboratory almost immediately after excavation (Fig. 1) before sampling. In the photographs the more water saturated (wet) regions appeared as relatively dark. This paper will first describe the image processing performed to combine the different photographs into a single gray-scale map of the bentonite surface. It will then explore the correlation between this map and the laboratory measurements of water content at the sample locations before it tries to leverage the observed correlation to arrive to a finer reconstruction of the water content profile. This map of water content is of great interest as it should provide information on the original number, location and transmissivity of intersecting flow channels in the rock. In addition, this final state of water content in the bentonite parcel together with time series of embedded humidity sensors, could also possibly indicate how flow channels might have been dynamically redistributed in time over the bentonite/rock interface when the buffer wetting was under way. This kind of dataset should help improve the flow models for the natural rock barrier and give better estimates of the operating conditions for the bentonite buffer, which could in turn help buffer design. The question we would like to answer in the present paper is whether it is possible and informative to combine the sampling data and the photographs of the bentonite parcel to obtain increased resolution of the water content profile on the bentonite surface at the end of the experiment. A detailed distribution of the water content at the bentonite surface in contact with the rock would greatly help to understand the impact of flow channeling and two-phase flow behavior in fractured crystalline rock under high suction, and subsequently to assess the hydraulic conditions imposed on engineered barrier system. Combining the rapid execution and wide coverage of photographs with accurate local sampling would appear as a cost-effective technique to acquire such a fine scale distribution. To the extent of our knowledge, investigations related to the direct use of photographs in order to quantify the in situ water uptake of bentonite parcels in natural bedrock have not yet been published in scientific literature.

Fig. 1. Example photograph of the Hole 18 bentonite parcel. The bentonite parcel height visible in the picture is about 1 m. The thin horizontal circular rings are the limits between different numbered compacted bentonite blocks (each of about 10 cm height except block 2). The thin vertical black line is the 0° reference line with increasing angles clockwise in the figure. Other dark patterns are believed to correspond to rock fracture traces (credits: Mattias Åkesson and Clay Technology).

2. Data and methods

This section will first provide details on the two sources of data available on the cylindrical bentonite parcel: samples and dismantling photographs. We focus on the gravimetric water content w profile that developed in the bentonite parcel after exposure to

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