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Hydrogeological characterisation and stochastic modelling of a hydraulically conductive fracture system affected by grouting: A case study of horizontal circular drifts

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ABSTRACT

Knowledge of the flow characteristics of the hydraulically conductive fracture system is important when planning grouting measures for underground openings, although investigations and data analyses may, for different reasons, provide uncertain information. The primary focus of this paper is to establish a conceptual description of the flow properties of a hydraulically conductive fracture system and to use it to evaluate the suitability of hydrogeological investigation methods and grouting designs proposed for a horizontal repository design (KBS-3H). Data from the KBS-3H experimental site, located at the Äspö Hard Rock Laboratory in Sweden, were gathered and analysed to characterise the hydraulically conductive fracture system and to produce a stochastic model for predicting fracture transmissivity distributions. The rock mass at the site was affected by pre-grouting activities. It was, however, still possible to recognise two categories of inflow features: the main hydraulic conductors, which could be identified reasonably using short-duration borehole tests, and the less conductive part of the fracture system (host rock) where the flow configuration could not be captured by the conducted borehole tests. Characterising the flow properties of both categories is deemed important when developing efficient grouting designs. Consequently, careful consideration must be given during the design phase to the choice of data acquisition method and its implication for characterisation and modelling. The collection of suitable, strategic data is identified as a prerequisite for the reliable prediction of the flow properties of a fracture system.

1. Introduction

Techniques for deep storage of spent nuclear fuel in crystalline granitic rock masses are currently being evaluated by the Swedish Nuclear Fuel and Waste Management Company (SKB) in Sweden and Posiva Oy in Finland. The reference layout for the deep repository in Sweden is based on vertical emplacement of the waste canisters (KBS-3V) although an alternative layout with horizontal emplacement (KBS-3H) (shown in Fig. 1) is also being studied (SKB, 2010a,b). The horizontal concept consists of parallel deposition drifts with a diameter of 1.85 m and a maximum length of approximately 300 m. Multiple canisters will be placed in these drifts, separated by blocks of bentonite buffer (Autio et al., 2008; SKB, 2012).

There are established deposition criteria that relate to avoidance of intersection with large and/or highly conductive fractures (SKB, 2010b, 2011). In addition, there are criteria for a permissible inflow of groundwater into full-length drifts and individual drift sections. These inflows affect the production rate and operational safety and may potentially lead to unfavourable implications for long-term safety due to mechanical erosion of the buffer (SKB, 2011). Canister deposition is not permitted in sections exceeding the target values for acceptable inflows. However, inflow reductions in these sections can create better conditions for the installation of engineered components during the operational phase (SKB, 2012). Consequently, plans are in place for the use of groundwater control techniques, such as grouting. The grouting can either be carried out as pre-grouting in pilot boreholes before reaming these to full drift diameter, or as post-grouting inside the drifts after excavation.

Decisions related to the reaming of the pilot hole to full drift diameter, and if so, how to apply suitable grouting designs, are based on integration of existing information and observations of inflows into the pilot borehole (SKB, 2012). However, geological and hydrogeological investigations have limitations and may, for various reasons, provide uncertain information. Borehole measurements suffer from limitations, i.e. spatial restrictions leading to orientation and sampling bias, effects of drilling-induced damage, and censoring of data due to measurement resolution limits (Berkowitz, 2002; NRC, 1996). Moreover, the small samples provided in boreholes are not necessarily representative of the surrounding

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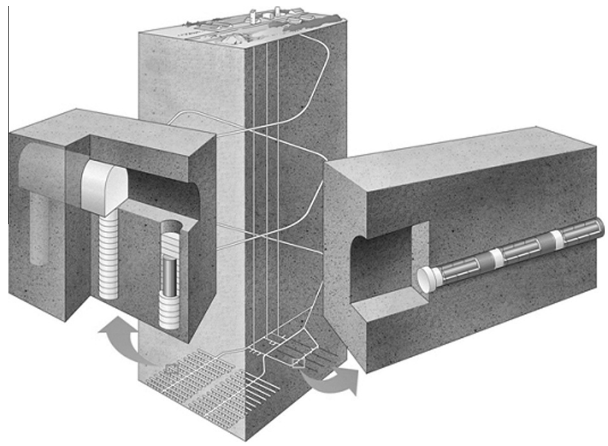

Fig. 1. Principle of the KBS-3 repository design concept, with the vertical deposition alternative (KBS-3V) and the horizontal deposition alternative (KBS-3H) (SKB, 2012).

rock mass and may initiate inappropriate extrapolations. Nevertheless, borehole measurements are considered useful for characterising fractures and fracture flow, especially when integrating several test methods and using an adequate conceptual model of the rock mass (NRC, 1996).

SKB has been involved in a number of studies where predictions of inflow based on borehole investigations have been a component, e.g. the Site Characterisation and Validation (SCV) project at Stripa (Olsson and Gale, 1995) and the Prototype Repository Test at the Äspö Hard Rock Laboratory (HRL) (Rhén and Forsmark, 2001). There have also been studies that focus more specifically on grouting, e.g. the TASQ Tunnel project (Emmelin et al., 2004), the TASS Tunnel project (Funehag and Emmelin, 2011), and the KBS-3H post-grouting project (Eriksson and Lindström, 2008). Uncertainties still remain about how to accomplish efficient hydrogeological characterisation as input for grouting design, especially characterisation and grouting that is adapted specifically to the KBS-3H repository design (Autio et al., 2008; SKB, 2012). Understanding the characteristics of a hydraulically conductive fracture system and its influence on the groutability is considered essential for the establishment of efficient grouting designs, see e.g. Fransson (2001) and Hernqvist et al. (2012).

The primary focus of this paper is to establish a conceptual description of the flow properties of a fracture system and use it to evaluate the suitability of hydrogeological investigation methods and grouting designs proposed for the KBS-3H repository design. The data studied are generated from investigations and grouting activities carried out at the KBS-3H design development site, located at the Äspö Hard Rock Laboratory (HRL) in Sweden. The main part of the data is affected by pre-grouting activities. It is, however, still possible to investigate a set of functional parameters to describe the rock mass for grouting purposes. The influence of various flow configurations, test scales, and test methods on inflow and grouting prognoses has been considered and suggestions for future implementation of hydraulic tests and grouting activities have been provided. The basis for the conceptual description is a hydrogeological characterisation of the hydraulically conductive fracture system and the use of a stochastic model for predicting fracture transmissivity distributions.

2. Materials and methods

The investigated rock volume is the KBS-3H experimental site located at the 220 m level at the Äspö Hard Rock Laboratory (HRL). The underground laboratory is situated in crystalline bedrock on the east coast of Sweden and is a research facility managed by the Swedish Nuclear Fuel and Waste Management Company (SKB). The experimental site was developed for the demonstration phase of KBS-3H design development in 2004–2007. The phase included practical trials aimed at demonstrating the technical feasibility of the horizontal deposition alternative and focused on KBS-3H-specific issues, such as the constructability of the drifts and execution of post-grouting measures (Autio et al., 2008; SKB, 2012).

Various geological investigations and hydraulic tests have been carried out in boreholes and demonstration drifts at the KBS-3H site during the demonstration phase (described in Section 2.3). In this study, these data were analysed to characterise the hydraulically conductive fracture system and to apply an analytical model for predicting fracture transmissivity distributions. The prediction constructed using the stochastic model, based on borehole data, was compared with the measured outcome in the excavated drift. The method used to characterise the hydraulically conductive fracture system and the transmissivity modelling are described in Sections 2.1 and 2.2, respectively.

2.1. Characterisation of a hydraulically conductive fracture system

The characterisation conducted in this study focused on the hydrogeological behaviour of the rock mass. It was based on work presented by Hernqvist (2011) and Butrón (2012), both of whom discussed conceptualisation of a hydraulically conductive fracture system relevant to both water inflow prognoses and grouting design. Hernqvist (2011) identified a set of functional parameters to describe crystalline rock masses for grouting purposes: *fracture frequency*, *the number and orientation of major fracture sets*, *hydraulic apertures of fractures based on transmissivity*, *flow dimension* and *hydraulic head*. A combination of geological mapping and hydrogeological measurements is needed to quantify these parameters and describe them qualitatively.

The fracture frequency (also referred to as fracture intensity) is a measure of the number of fractures in the rock. It could be described using the scale-independent parameter P_{10} (m^{-1}), which is a measure of the number of fractures per borehole length (Dershowitz and Herda, 1992). P_{10} can be obtained from geological mapping of drill cores with additional information from Borehole Image Processing Systems (BIPS). With this information, it is also possible to identify fracture orientations and determine whether fractures are open or sealed. This can in turn be used to identify the geometry and properties of fracture sets. Important subcategories of the linear fracture frequency include the frequency of all open fractures along a borehole, $P_{10,open}$ (m^{-1}) and the frequency of hydraulically conductive fractures, $P_{10,water}$ (m^{-1}).

Measurements of hydraulic head and quantification of the properties of hydraulically conductive features can be made using various hydraulic tests performed underground. Short-duration tests, such as water inflow measurements and water injection tests, assume steady-state conditions and represent local conditions around the borehole. Pressure build-up tests (PBTs) measure the transient pressure recovery after a flow period in boreholes or borehole sections, and may reflect hydraulic conditions for more remote parts of the fracture network if test periods last sufficiently long (e.g. Ludvigson et al., 2007).

From hydraulic tests, it is possible to evaluate the transmissivity, T, (m^2/s), which governs the water transport capacity of a rock mass to a specific borehole (Gustafson, 2012). The term may also be used as a measure of the ability of a fracture to transmit water (fracture transmissivity, T_f). A reasonable estimation of the transmissivity can be obtained from short-duration hydraulic tests by evaluating the specific capacity, $T \approx Q/dh$ (Fransson, 2001). The