A FRACTURED AQUIFER AND ENGINEERED BARRIER - METHODS AND TOOLS OF AN EVALUATION

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Abstract: *This paper outlines the results of a four year project that has examined small-scale fluid migration within a fractured granite aquifer. The features of the rock environment have been intensively studied under both laboratory and field conditions. A highly accurate three dimensional model of the site was constructed. The measured and predicted results have been compared and model reliability discussed.*

Introduction

A four-year project entitled “Methods and tools for evaluating the effects of engineered barriers on distant interactions in the environment of a deep repository facility” emerged from a need to provide safe long-term radioactive waste disposal within the rock environment. Safe waste disposal requires that the radionuclides are fixed within the underground site and that this is sealed by barriers. These barriers are provided by sealing materials that are usually based on natural geotextiles.

This paper presents an outline of the project and its main conclusions. It is, unfortunately, not possible to describe the background and results of the entire project here. The project had two major goals. The first was to design methodological procedures that could evaluate the effectiveness of barriers that may be applied to inhibit fluid migration within a fracture system. The second was to demonstrate that the effectiveness of the applied barriers could be predicted from a model. The project was undertaken at the smallest possible scale in order to characterise the fracture network in detail.

The features of the rock environment were studied in both laboratory and field settings. The field experiments were undertaken in a granite quarry, which also provided the samples used in the laboratory tests. Clearly defined man-made fractures in different samples were described and tested in the laboratory. Subsequently, a range of natural and artificial barriers were applied in controlled circumstances. The granite and experimental results were then described using mathematical modelling tools [1]. After careful geological and geophysical research, a small geologically simple area was selected in the quarry. Fourteen short boreholes were studied [2]. To constrain the hydrogeological features, regime monitoring, pumping, sludge and cross-hole tracer tests were undertaken. Thereafter, a descriptive three dimensional mathematical model was constructed. Barriers that can be used for fracture grouting were applied and additional tracer tests were subsequently undertaken. A descriptive model of the site was used to predict the results of the tracer tests. The measured and predicted field results have been compared.

Geological setting

Prior to any other work, a suitable locality had to be selected. A comprehensive understanding of the local fracture system was critical. It was essential that this network was easy to characterise so that the chances of errors caused by inaccurate network description in the later modelling could be minimised. Following careful consideration, Panské Dubenky Quarry in the Czech Republic was chosen because the fracture system there is sufficiently straight to be precisely described in detail (Fig. 1).

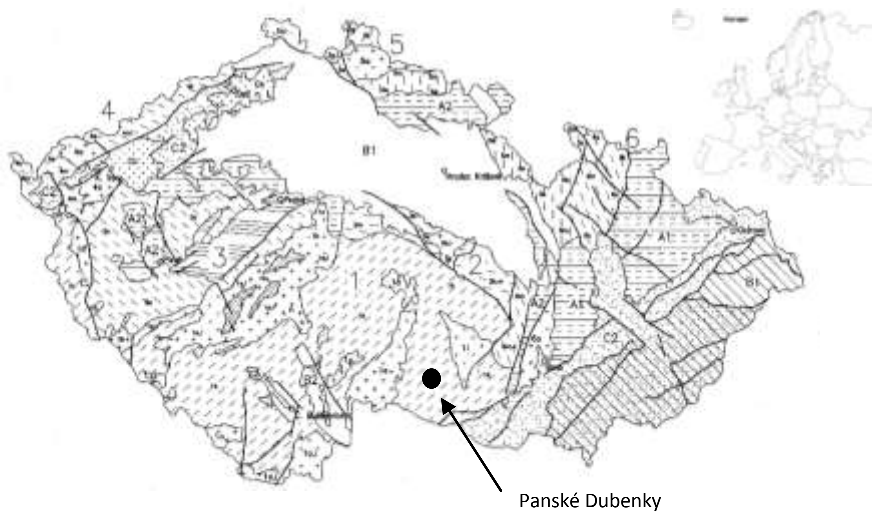

Fig. 1 The location of Panské Dubenky Quarry on a schematic geological map of the Czech Republic (major areas of the Bohemian Massif: 1 - moldanubikum, 2 - Kutna hora – Svratka area, 3 – barrandien, 4 – saxothuringikum, 5 - lugikum, 6 - silesikum, A, B, C – postvariscian sediments, modified after [3]).

Panské Dubenky Quarry is situated in the large Variscian Bohemian Massif of central Europe. It is specifically located within the major regional geological unit, the Central Moldanubic Massif. Petrographically, composition of this unit is quite monotonous. The rocks are mainly Eisgarn binary granites, characteristic by similar amounts of plagioclase and potassic feldspar. Two varieties of granite were found in the quarry, a fresh grey granite and a slightly weathered yellow granite. In spite of this, the granite body within the quarry is rather homogenous. The internal fracture network is comparatively simple and regular as a result of slow solidification in the post-tectonic era (it is for this reason that the quarry was selected). The most important regional joints are orientated 90-120° (Q-joints) and 0-30° (S-joints) [4]. However, diagonal joints orientated NE-SW and NW-SE are also present [5]. Most joints are not mineralised although some of the joints have thin coatings of Fe-oxides. If any mineralisation has occurred, it is unusually mylonitic; occasional chlorites, quartz and feldspar crystals can also be found. In some places it is possible to observe tiny outflows of water in the fresh quarry face.

The project

The project lasted for four years. During this period, a wide range of rock environment characteristics was studied simultaneously. Unsurprisingly, a great number of tests and experiments have been undertaken. The laboratory tests and experiments depicted the basic characteristics of the granite, the fracture network, and several barriers. The geochemical properties of the granite were studied to identify any mechanism, such as sorption, that may influence the movement of tracers within the rock environment.

Three types of granite sample were tested in the laboratory (Fig. 2). The first were cylindrical samples with heights of 150 or 200 mm and diameters of 88, 105, or 137 mm; these samples were either tectonically intact or had been affected by fractures (open or healed). The second were matching ctenoid ("comb-like") samples that were constructed from a pair of granite blocks (800 x 600 x 300 mm). The third were cuboid block samples with natural fractures (base 250 or 600 mm).

Fig. 2 The three types of laboratory samples: cylindrical (left), ctenoid (centre), and block (right).

The laboratory work included measuring the physical properties of the granite (porosity, specific gravity, and ultrasound-waves velocities with a frequency of 1 MHz), hydrodynamic and fluid migration tests, and describing the overall character of the investigated discontinuities (geometry and opening). Hydrodynamic tests were carried out on each of the sample types. The tests were conducted under stationary convection and constant hydraulic gradient conditions, within a saturated environment. These tests resulted in volume flow rates and hydraulic conductivity coefficients. The tracers, NaCl-solutions and Na-Fluorescein, were detected by electric conductivity measuring. The radiance of the tracer in blue light was used to determine penetration curves for each of the tracers. The theoretically suitable natural (bentonite) and artificial (geotextile) barriers for fracture grouting were both studied. The specimens were subjected to tests that could determine their compressive strength and hydraulic conductivity coefficient. The block and ctenoid samples were partially grouted with the selected barrier and the hydrodynamic and migration tests were duplicated under the same conditions. These tests resulted in volume flow rates, barrier hydraulic conductivity coefficients, and penetration curves for each of the tracers.

The attained data allowed preliminary mathematical modelling and subsequent fieldwork planning. Initially, fieldwork was focused on accurately defining the fracture network in Panské Dubenky Quarry. Sequentially, the precise location of a small test polygon was decided upon. The polygon covered ~ 400 m^2 and incorporated fourteen shallow boreholes with depths of between 7 to 10 m. A highly accurate model of the fracture network within the polygon was then constructed from detailed structural research, borehole inspection, seismic data, multi-electrode resistivity profiling, pumping, sludge and tracer tests. The cross-hole tracer tests [2] were used to calibrate the joint opening parameters within the fracture network for the mathematic modelling. Following the construction of the fracture network model, three boreholes were partly sealed using a bentonite-based barrier and then another set of cross-hole tracer tests were performed.

Mathematic modelling

The main aim of the project was to draft, test, and describe a methodical procedure of hydrogeological survey and mathematical modelling within a fractured granite environment both with and without engineered barriers. Therefore, mathematical modelling formed an integral part of the project from the outset. Initially, suitable software was sought. It was critical that this software could give a discrete description of the fractures with respect to the natural heterogeneity and anisotropy of the environment. The software also had to have been previously used and validated in other international projects related to waste disposal in crystalline rocks. After extensive consideration, two software codes were chosen: NAPSAC and FEFLOW.

During the project, NAPSAC was used as the primary application for modelling the geometry, convection, and transport of the discrete fracture networks. The only significant disadvantage was the absence of algorithms capable of transient simulation analysis in variably saturated environments (this problem has been addressed in the latest version the software, NAPSAC 9.8). In contrast, FEFLOW allows single joints to be entered in the porous or impermeable environments. It is not capable of geometrically authentic single joint or fracture network simulation. However, it does allow simulation of convection and transport within the fractures filled with porous material. This programme was used mainly for simulation at the laboratory scale and for assessing the influence of the applied barrier. Both NAPSAC and FEFLOW performed well during the project and fulfilled the role that they had been chosen for.

To obtain relevant and reliable results, a number of laboratory and field simulations were conducted. A number of granite samples had been tested in the laboratory both with or without fractures and before and after barrier construction. The laboratory tests provided insight into the properties of the intact and fractured granite at the small scale. In addition, the tests provided information that could be used to define the instrumental and measuring strategies implemented during the field experiments.

Analogical simulations tested both programs. A proper methodology was set for simulation at the requisite scale that allowed alternative an entry parameter inlet and model calibration. Due to the fact that modelling within discrete fracture zones is not a common hydrogeological task, it was very important that the laboratory work was able to underpin the model.

The significant number of tests and types of geological measurements undertaken in the polygon allowed both programs to construct a discrete deterministic geometric model of the fracture network. The tests also provided enough information to calibrate the rheostatic parameters of every single joint within the network (Fig. 3).

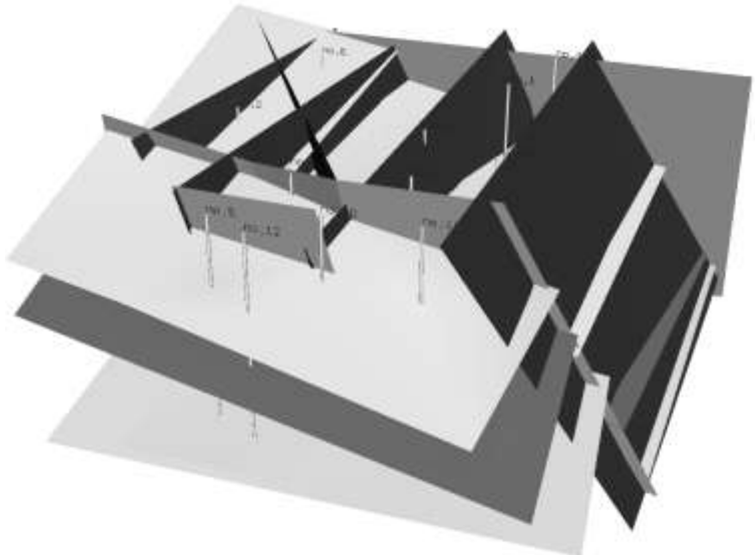

Fig. 3 A model of the discrete fracture network, including rheostatic parameters.

Setting the migration parameters was more difficult because less data had been obtained through direct measurements. Therefore, it was necessary to simplify these parameters more. Nevertheless, the analogical and predicted simulations undertaken on the basis of experiments with artificially created gradients were found to be quite accurate. But during the simulation of tests undertaken by applying the natural groundwater flow regime, greater inaccuracies were observed because of the imprecise formulation of conditions on the model domain boundary. These marginal conditions could not be set for the test domain. Therefore, the model calibration of boundary conditions on the basis of transient pumping tests was only approximate.

Lessons learned

A number of important lessons have been learnt during the project. First, various methods of geological, geophysical, and hydrogeological survey in fractured granite environment have been evaluated. A methodical procedure for the construction of a discrete fracture network model has been suggested. Second, further experiments were found to be valuable in order to construct a reliable predictive model. Third, the characteristics of possible barriers for fracture grouting have been described. The influence of the barriers over migration parameters has also been shown. Fourth, the predictive model was applied and tested. The model was validated through a series of blind tests (Tab. 1). The results of these tests reveal a high level of predictive reliability. However, it is essential to set realistic expectations for the predictive model.

Tab. 1 A comparison of the results from the predictive model and cross-hole tests

<table>
<tr><th colspan="2"></th><th>Test 1</th><th colspan="2">Test 2</th></tr>
<tr><td>Difference in water level between the wells during the test [m]</td><td></td><td>6.66</td><td colspan="2">3.5</td></tr>
<tr><td rowspan="2">Water flow [$l.s^{-1}$]</td><td>Model</td><td>$1.3*10^{-2} l.s^{-1}$</td><td colspan="2">$1.6*10^{-5}$</td></tr>
<tr><td>Test</td><td>$6.2*10^{-3} l.s^{-1}$</td><td colspan="2">**$8.9*10^{-6}$**</td></tr>
<tr><td rowspan="3">Time taken for the tracer to arrive [s]</td><td rowspan="2">Model</td><td rowspan="2">139</td><td>Path A</td><td>493.1
(= 20.5 d)</td></tr>
<tr><td>Path B</td><td>29.8
(= 1.24 d)</td></tr>
<tr><td>Test</td><td>135</td><td colspan="2">**55.8 (=2.32 d)**</td></tr>
</table>

Acknowledgements

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