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# Methodology for the hydraulic characterization of a granitic block

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**Abstract** Geometrical, geological and hydrogeological data are integrated in the hydrogeological study of the FEBEX experiment. Integration includes both local and regional scale elements (from tens to hundreds of metres) affecting groundwater flow towards the engineered barrier. The objective is to develop a numerical model capable of predicting the gallery inflow and giving a quantitative explanation of the distribution of hydraulic parameters through the rock volume affected by the experiment. Geological characterization is based on the description of cores from 23 observation wells, as well as the mapped gallery and adjacent tunnels, geophysical studies and pressure data from all well intervals, and discharge measured at different points. Single borehole instantaneous injection tests were performed at all intervals with packers; five cross-hole tests were done as well, recording the pressure responses at many observation points. All these data were finally integrated in numerical models, together with steady state head measurements and flow discharge values at the gallery. One of the most remarkable aspects in this study is the consistency among hydraulic parameters obtained by different methods, despite the appearance of scale effects. A joint analysis of results produced by several models throughout the project has been performed.

## INTRODUCTION

This paper is a summary of the characterization work in a low permeable granite block located at the Grimsel underground laboratory (Switzerland). The work was conducted within the framework of the international project FEBEX (Full Scale Engineered Barrier Experiment), aimed at demonstrating the viability of a bentonite barrier to store high-activity radioactive waste. Knowing the hydration degree of such barrier is essential and requires an accurate determination of the water flow towards the tunnel, of its distribution and of the hydraulic parameters.

This work has the following objectives: (a) to obtain the spatial distribution of flow and an estimate of its magnitude; (b) to derive a hydrogeological conceptual model of the experiment area; (c) to assess the hydraulic boundary conditions for hydrothermal modelling; and (d) to develop a numerical model of the water flow before the start of the heating experiments.

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The paper is organised as follows: (a) general description of available data, (b) integration of these data to generate a conceptual model, (c) preparation of the numerical model, and (d) discussion of results obtained in all the tests throughout the project. Special emphasis is placed on evaluating the consistency among different characterization methods because, on a cursory analysis, conductivity data appear to display scale effects.

## DESCRIPTION OF AVAILABLE DATA

The site of the FEBEX experiment was explored with 23 boreholes of depths ranging from 7 to 151 m (Fig. 1). The available data consist of a geological map of the tunnel wall, the borehole configuration, core descriptions and head monitoring in boreholes at several depths.

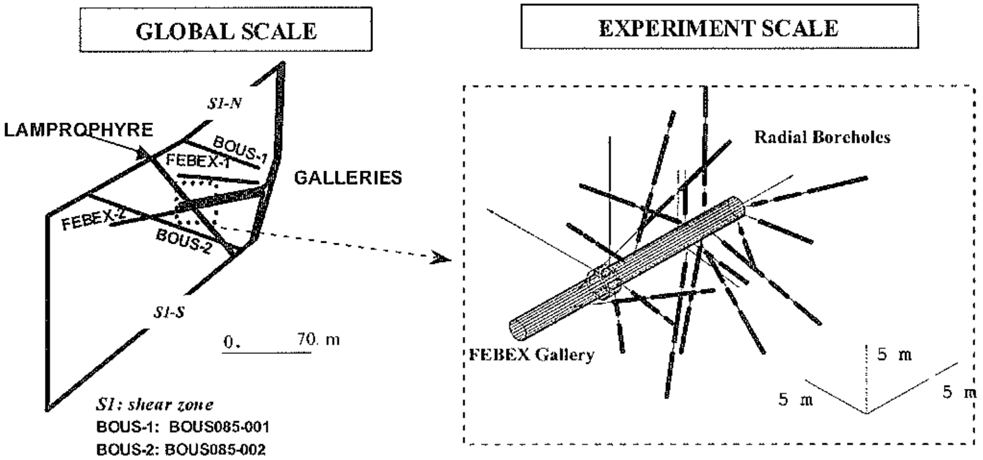

**Fig. 1** Situation of the experiment zone, at different scales.

**Geological map** Mapping of different structures and formations intercepting the tunnels, including descriptions and photographs of well cores.

**Geophysics** Seismic tomography as well as a georadar measurements were carried out between the wells BOUS085-001/.002 and .003. Results displayed a weak correlation with observed hydrogeological data.

**Inflow measurements at the tunnel wall** A new method for measuring the inflow to the tunnel walls was developed due to the need to obtain reliable measurements more easily (Guimerà *et al.*, 1996). The method consists of installing some layers of absorbing material (cellulose), with a known dry weight, at the tunnel walls for a certain period of time. Then, the material is weighed. The flow rate can be evaluated as the weight difference divided by time.

**Hydraulic borehole measurements** All boreholes are equipped with packers in order to isolate the main structures from the rest of the well. Each depth has a pressure sensor that automatically registers the piezometric heads.

**Hydraulic tests** A series of hydraulic tests were conducted at different depths and with distinct objectives. Tests included hydraulic tests *sensu stricto* (pulse, cross-hole tests) but also the response of the heads to perturbations such as the construction of the tunnel and boreholes, and the ventilation of the galleries.

The cross-hole tests in radial boreholes must be highlighted. The objective was to characterize the area in the vicinity of the experiment (the last 20 m of the tunnel, Fig. 1). Five tests were conducted to achieve this, by pumping at one depth and measuring the response at all the depths (42 observation points).

## HYDRAULIC TEST INTERPRETATION

The interpretation of the five cross-hole tests was carried out by means of:

- Conventional interpretation using the Theis model implemented in the code MARIAJ-IV (Carbonell *et al.*, 1997). First an analysis of the drawdowns was made at the depths that were sensitive to the pumping. In general the transmissivity estimates ($T$) at the observation well are very similar for each pumping test, whereas the estimated storage coefficients ($S$) vary by orders of magnitude (Table 1). Meier *et al.* (1998), attribute this effect to the spatial variability, which is extremely high in this kind of media. The estimated storage coefficient is indicative of the connectivity between the pumping and the observation point: a low storage coefficient indicates a high connectivity, and *vice versa*.
- Interpretation of each long term pumping test with a three-dimensional (3-D) inverse numerical model (using TRANSIN-III code, Galarza *et al.*, 1996), that includes the main heterogeneities of the medium and is calibrated automatically by using simultaneously the drawdown measurements at all observation points.

**Table 1** Parameters, calculated by conventional interpretation, for one of the five cross-hole tests. Note that the $T$ estimates show a homogeneous distribution in contrast to the storativity estimates, $S$. A small storativity estimate indicates a point that is strongly connected with the pumping well (F22.2 about 40 m drawdown, like the pumping point).

| Pumping point | Observation point | Drawdown (m) | $T$ (m$^2$ s$^{-1}$) | $S$ |
|---|---|---|---|---|
| I2.1 | I2.1 | 40 | $1.1 \times 10^{-9}$ | $1.5 \times 10^{-5}$ |
| | F12.1 | 3 | $1.4 \times 10^{-9}$ | $6.2 \times 10^{-6}$ |
| | F12.2 | 8 | $1.4 \times 10^{-9}$ | $6.7 \times 10^{-6}$ |
| | F12.3 | 15 | $1.2 \times 10^{-9}$ | $1.1 \times 10^{-6}$ |
| | F22.1 | 11 | $1.1 \times 10^{-9}$ | $5.4 \times 10^{-7}$ |
| | F22.2 | 40 | $8.1 \times 10^{-10}$ | $1.1 \times 10^{-8}$ |
| | F22.3 | 17 | $7.7 \times 10^{-10}$ | $2.1 \times 10^{-6}$ |

## JOINT INTERPRETATION OF ALL DATA: CONCEPTUAL MODEL

The following step consists of the joint interpretation of all the data to obtain the conceptual model. The identification of the main structures is relevant because they condition the flow distribution in the area.

From the study of the geological/structural mapping of the tunnels and borehole cores it is possible to obtain the geometry of the geologically relevant structures (dykes, shear zones, isolated fractures). A purely geometric correlation can be deduced with the help of geophysics, i.e. the position and relationships of the existing structures can be physically identified.

The effect of perturbations (hydraulic tests, tunnel ventilation, well drilling, etc.) on heads are used to gain insight into the hydraulic connectivity between layers and the possible extension of the fractures. More importantly, how fast an observation interval reacts to pumping is the best indication of connectivity. This can be quantified by means of the storativity derived from an interpretation using the Jacob method (Meier *et al.*, 1998). This methodology allows one to disregard the hydraulically unimportant structures among the initially identified features.

## MODEL CONSTRUCTION

Several numerical models, are built based on the existing conceptual model. A 3-D finite element mesh is generated, where the geometry is superimposed. Geometry is represented by 3-D elements (dyke, rock), 2-D elements (fractures) and 1-D elements (boreholes) (Fig. 2).

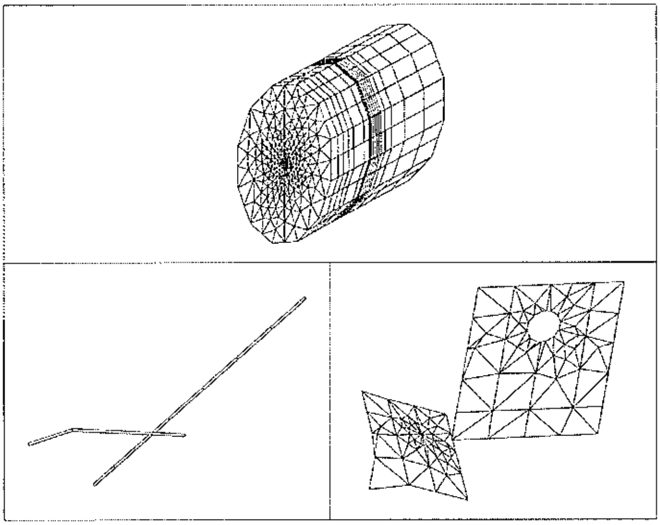

**Fig. 2** Scheme of the different types of elements forming the finite elements mesh. Top: rock matrix (3-D elements). Bottom left: boreholes (1-D elements). Bottom right: some fracture plains (2-D elements).

Prior information is taken from the conventional interpretation of the tests. This is used for the interpretation of the cross-hole tests with three dimensional models, in order to represent the heterogeneities and calculate the hydraulic parameters of the main structures.

After automatic calibration, the sets of parameters obtained with the interpretation of the different tests are compared and unified. A final calibration is then performed with this unique set of parameters, which is consistent with the conceptual model.

The results of the interpretation of cross-hole tests (3-D interpretation) were used as prior information and initial parameters for the steady state flow model of the experimental zone.

The main structures, boreholes and gallery were also explicitly included in the model.

## COMPARISON AMONG PARAMETERS

Throughout the project different types of hydraulic tests were conducted, followed by the corresponding interpretations. The hydraulic conductivities obtained are compared here. Figure 3 shows the values of hydraulic conductivity as derived from four different interpretation methods (pulse tests, Horner build-up tests, cross-hole tests, integrated models), indicating the relative scale.

Pulse and Horner tests involve a small rock volume (+), because they only affect the immediate vicinity of the borehole. Since they were performed in all the borehole intervals, a large number of tests display low hydraulic conductivities. However, a few points deviate from the average, probably due to an intersection with a more conductive zone (i.e. a fracture). The mode for the pulse test is about $10^{-11}$ m $s^{-1}$, while the mode for Horner tests falls at $5 \times 10^{-11}$ m $s^{-1}$. The increase, probably, reflects the role of fractures near the borehole.

Cross-hole tests affect a larger rock volume. The five available tests are indicated by the vertical lines. Based on the interpretation approach we have:

- Symbol × represents the conductivity obtained by means of the code MARIAJ-IV. The average length of the intervals (5 m) was used to convert from trans-missivity into hydraulic conductivity. Note that the transmissivity derived from the Theis (or Jacob) model is one to two orders of magnitude larger than the mode of small scale values.
- Interpretation with 3-D models (TRANSIN-III code), which also treat the medium as homogeneous and isotropic but explicitly incorporate discrete fractures. A

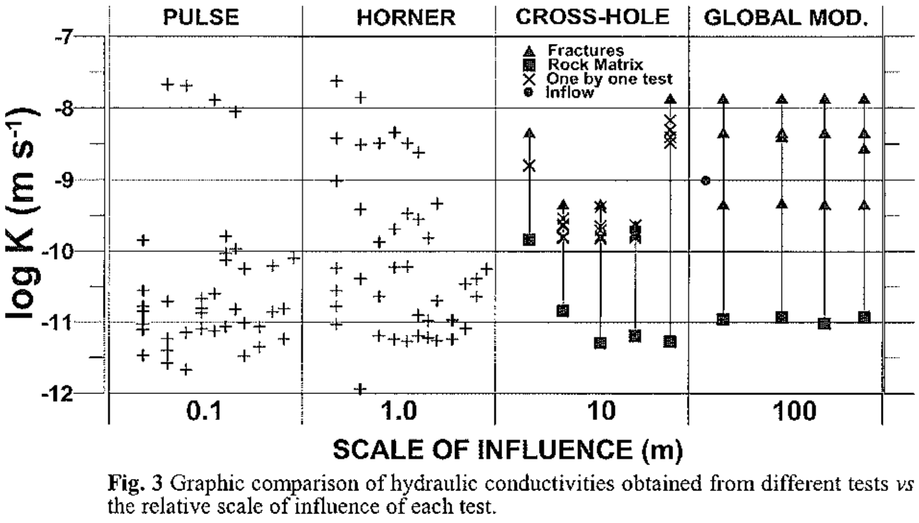

**Fig. 3** Graphic comparison of hydraulic conductivities obtained from different tests *vs* the relative scale of influence of each test.

distinction is made in Fig. 3 between the hydraulic conductivity of the formation (▣) and the fractures (▲). Notice that fracture transmissivities derived from calibration are slightly larger but comparable to those obtained from Theis interpretation. The mode now falls around $5 \times 10^{-10}$ m $s^{-1}$.

- The regional scale models (large scale) were interpreted like the cross-hole tests, i.e. by means of 3-D homogeneous and isotropic media with discrete fractures. Inflow measurements into the test tunnel are well reproduced by this model. The equivalent homogeneous conductivity is of about $5 \times 10^{-9}$ m $s^{-1}$.
- Symbol ◉ represents the measurement of the inflow to the FEBEX gallery, calculated using this rate, gradient measurement and assuming a tunnel length of 13 m, the transmissivity was estimated to be about $10^{-9}$ m $s^{-1}$.

Such results indicate that:

- The one at a time interpretation of the cross-hole tests yield higher conductivity values than the pulse and Horner tests. In fact, representative values of hydraulic conductivity increase from $10^{-11}$ (pulse) to $5 \times 10^{-11}$ (Horner) to $5 \times 10^{-10}$ (cross-hole) to $5 \times 10^{-9}$ (inflow).
- Matrix and fracture conductivities calculated with the 3-D models are comparable to those of the pulse, Horner tests and cross-hole tests.

## CONCLUSIONS

The use of 3-D models allows for an integration of all the acquired data throughout the project. This enhances the robustness of the model.

The conductivity increases as the test scale affects a larger rock bulk volume. As a consequence, those tests involving a small volume of rock (pulse, Horner), yield the matrix conductivity, whereas when the affected volume increases we obtain the conductivity of the dominant fractures. However, this is no longer true if it is possible to separate the more conductive fractures from the rock matrix. In fact, as long as the most relevant hydrogeological features are taken into account in 3-D models combined with the rock matrix, results are consistent with those obtained by the small scale tests.

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