Re-interpretation of the fluid electric conductivity measurements carried out in the MIZ-1 borehole at the Mizunami underground research laboratory project

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1. Introduction

As part of the surface based investigation phase of the Mizunami underground research project, the 1,350 meter long borehole MIZ-1 has been completed using directional drilling with the main purpose to characterize the geological environment over 1,000m depth in the crystalline basement (Toki granite). As part of the investigations fluid electric conductivity (FEC) measurements have been carried out.

FEC is a borehole geophysical technique which measures the electric conductivity of the borehole fluid along its length over time while water is being extracted after the borehole fluid has initially been replaced with a fluid with a conductivity contrasting with the formation fluid (Tsang and Hufschmied, 1988). When the FEC measurements are carried out at a single pumping rate, the location of inflow points, the flow rate and the concentration of the formation fluid can be identified. If FEC measurements are carried out at different pumping rates, the pressure and the transmissivity of each feed point can be calculated (Tsang and Doughty, 2003). Although FEC measurements have been carried out at different flow rates in the MIZ-1 borehole, the transmissivity of each inflow point had not been calculated. In this paper the data from the second FEC measurement campaign carried out in the MIZ-1 borehole will therefore be re-analyzed. As part of this project a new finite difference code has been developed for modeling the FEC curves using a dimensionless approach, as well as an automatic detection method for finding likely feed point locations.

Measurement data
↓
Preprocessing
↓
Feed point location
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Parameter estimation
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Hydraulic interpretation

Figure 1 Flow chart analysis FEC data.

2. Methodology

The general procedure for the FEC method is summarized in figure 1. The FEC method is a relatively simple method to carry out (figure 2). The formation water in the borehole is replaced by de-ionized water. The conductivity and the temperature of the fluid along the borehole are measured before pumping is started to obtain the initial conditions. After the pump is switched on the conductivity tool is moved up and down the borehole at regular time intervals to make measurements. The same procedure is then repeated with at least one other pumping rate.

In the preprocessing step the measured electric conductivities are temperature corrected before being transformed to an equivalent concentration of dissolved NaCl. If necessary the number of data is reduced and the curves are filtered to eliminate high frequency noise. The resulting curves show the concentration distribution with depth. As water is pumped from the borehole, formation water, with higher concentrations, will appear at distinct locations, initially showing up as peaks on the FEC curves.

All curves should be used to determine the location of the feed points, as certain feed points will not be visible on all curves. A computer program has been developed that detects the location of potential feed points by finding and rating local maxima from all curves, and presents a statistical analysis for each possible location. The final selection of feed points is however still up to the interpreter.

The goal in the modeling stage is to reproduce the measured curves by adjusting the flow rate and concentration at each feed point location with a specially developed finite difference code. The main difference with the BORE code developed by Tsang and

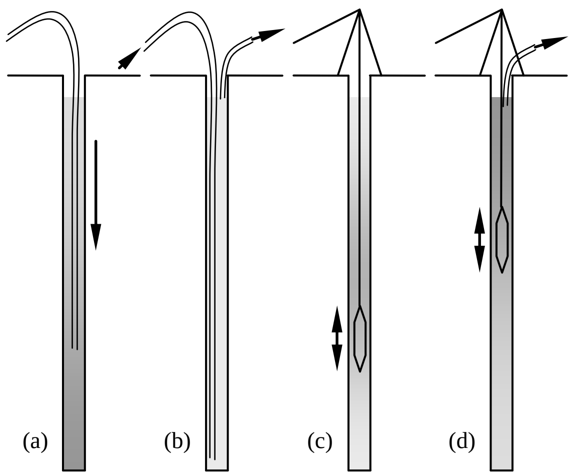

Figure 2 FEC test procedure: (a) insert tubing, (b) exchange water in borehole, (c) first FEC measurement run to determine initial concentrations, (d) turn on pump and collect FEC measurements at regular time intervals.

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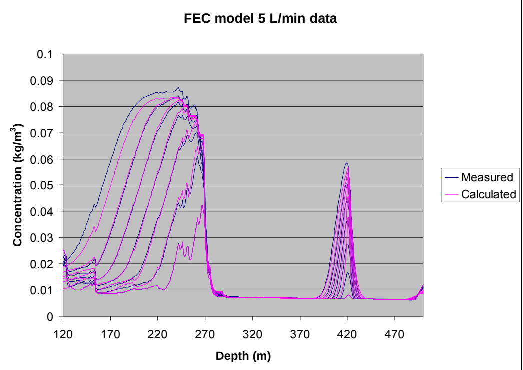

Figure 3 Measured and modeled curves at 5 L/min.

Hufschmidt (1988) is the usage of a dimensionless approach. This has the advantage that numerical errors are minimized and showed for instance through the Peclet number that the model is relatively insensitive to changes in dispersion, which allowed us to make a number of simplifying assumptions.

To find the best fit is a process of trial and error, and can be a daunting task. The number of possible solutions can however be quickly narrowed down by using the following balances: the sum of all feed point flow rates equals the pumping rate; the shift between curves at different times is proportional to the sum of all upstream feed point flow rates; the change in area below curves at different times divided by the sum of the upstream feed point flow rates is proportional to the concentration of a feed point. Exchanging the borehole fluid with de-ionized water can lead to mixing with formation fluid in the rock mass. This can cause problems at early times when the feed points produce diluted formation water. In our approach this problem has been solved by using one of the later concentration profiles as initial condition. In principle the feed point concentrations at different pumping rates should be the same. However, for the hydraulic interpretation in the next step only the feed point flow rates will be used. Small deviations of the concentration are therefore not problematic. In the last step the transmissivity and the hydraulic head deviation of each feed point is calculated using the feed point flow rates, the measured drawdown and the pumping rates.

3. Results of the evaluation of the 2nd FEC measurement campaign at the MIZ-1 borehole

Using the methodology described above the concentration curves at the pumping rate of 5 and 20 l/min have been modeled. Figure 3 shows the measured and modeled concentration curves at the pumping rate of 5 l/min. The results of the hydraulic interpretation are summarized in figure 4.

The two largest feed point flow rates are located 421 and 268 mabh according to the FEC evaluation. Borehole televiewer (BHTV) measurements show a single high conductivity feature about 5 meters long at around 420 meter. The interval 418.0-421.1 has been hydraulically tested twice. The tests yielded transmissivities of 1.7E-05 and 7.9E-05 m^2/s. The 3.4E-05 m^2/s resulting from the FEC calculations at 420 m is therefore a very good result. The isolated location of this feed point with respect to other feed points made it easy to correctly determine the flow rates at this location.

At the section 261-271 mabh, the BHTV results show a zone with about 10 parallel, large aperture fractures. The result of a packer tests carried out over the interval from 261.2 to 270.4 mabh showed a transmissivity of 5.8E-04 m^2/s. The FEC result, which is the sum of the transmissivities at the points 262 and 268, is 4.9E-05 m^2/s or about one order of magnitude lower. The discrepancy between packer test and FEC result might be explained by the overlap of many peaks in the interval 220-270 mabh or by clogging of the fractures over time.

A number of issues with the FEC method exist. During the exchange of the borehole fluid, de-ionized water can enter the formation and mix with the formation water. This can have an important impact on the FEC readings especially at early times or at low pumping rates. If the hydraulic head deviation of a feed point is larger than the drawdown due to pumping, water in the borehole can leak into the rock mass. Negative feed point flow rates can however not be interpreted with the methodology presented in this paper. For instance, at the locations 437 and 472 mabh, peaks only appear at the pumping rate of 20 l/min. The features which inflow rate is approximately one order of magnitude smaller than the largest inflow rate will be difficult to model correctly, especially just after such largest inflow feature.

A number of points of research remain such as the current model's inability to deal with negative feed point flow rates, the mixing of exchange fluid with formation water, or the effect of turbulence and transient flow.

4. Conclusion

FEC measurements collected at different pumping rates can be used to calculate the transmissivities of fractures intersected by a borehole. The obtained results are comparable to those obtained by hydraulic testing. The method can be valuable to help in the selection of locations for more detailed hydraulic tests. Under certain circumstances the method can be used as a low cost alternative to hydraulic testing.

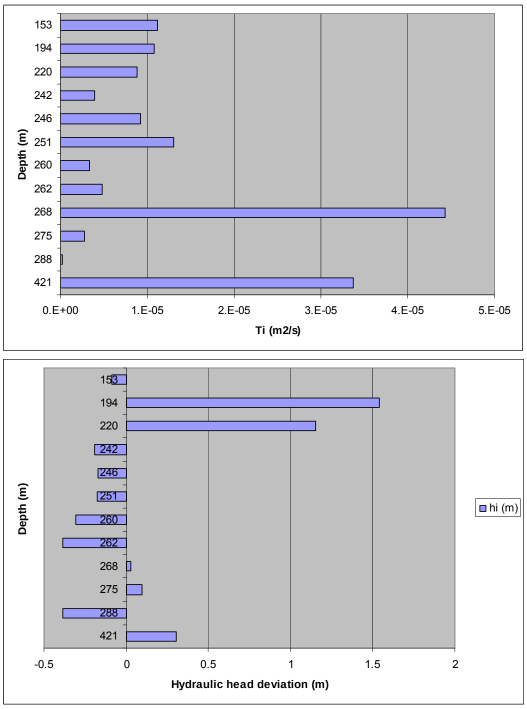

Figure 4 Transmissivity and hydraulic head deviation

5. References

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