# Hydrogeological characterisation and sealing of narrow fractures in hard rock - A case study

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**Abstract:** A field study was performed in a low permeable Swedish gneiss with few and narrow fractures. The study consisted of water loss measurements and grouting of the boreholes. The grout used was colloidal silica. The study indicates that colloidal silica can penetrate narrow fractures of at least an aperture of 0,04 mm

**Key words:** Colloidal silica, silica sol, chemical grouting, characterisation.

## Introduction

This paper evaluates the possibilities to use silica sol to seal or permeate fine fractures in hard rock. The increased demand on efficiency when sealing tunnels by grouting has led to a need to seal narrower fractures. The more conductive fractures are sealed by cement-based grouts, but the limitations in penetrability make these grouts less useful in low permeable rock. Colloidal silica is a new grouting material that has the ability to penetrate narrow fractures. The grout consists of two components, colloidal silica and salt solution, which both are environmentally sound. The salt solution (NaCl) acts as an accelerator.
A field study was conducted in November 2001 to investigate the penetrability of colloidal silica in a tight rock. It took place in the Southwest of Sweden in a niche at a transport tunnel at the island of Hisingen, Gothenburg. The rock was a low permeable gneiss with few and narrow fractures. Ten boreholes with a length of 4 m were drilled. Water loss measurements were conducted to estimate apertures of the fractures. The boreholes were grouted with colloidal silica and the penetration was estimated using the neighbouring boreholes. A mathematical model was derived to predict the results from the field study with theories describing the penetration. The penetration in field was then compared to the calculated penetration achieved from the numerical model.

## Characteristics of silica sol

Colloidal silica is a stable dispersion of discrete nonporous particles of amorphous silicon dioxide ($SiO_2$). Iler (1979) extensively describes the chemistry of colloidal silica. The viscosity of colloidal silica is initially very low and when the gelation starts, the viscosity grows rapidly. The geltime can range from a couple of minutes to several hours. The viscosity development at 8°C versus time with different mixtures of salt concentrations is shown in Figure 1. An exponential function is fitted to the viscosity curves achieved from the laboratory to mathematically treat these curves.

*Scientific paper*

## FLOW MODEL

The silica sol is considered as a Newtonian fluid with exponential growth in viscosity. The grout will penetrate a fracture with a specific width (aperture) and push the withstanding water in the front. Equation 1 below is derived to calculate the velocity of the grout (HÄSSLER, 1991).

$$\frac{dx}{dt} = \frac{\gamma_W \times b^2 \times (h_0 - h_L)}{12(\mu_W (L - X) + \mu_g \times X)} \quad (1)$$

Where: b= aperture, $\gamma_w$= specific weight of water, $h_0$-$h_L$= driving pressure, $\mu_W$= viscosity of the water, $\mu_g$= viscosity of the grout, L= discrete length of the fracture, X= distance to the front between the fluid and the grout.

An example of the penetration with use of Equation 1 is shown in Figure 2. The penetration is calculated at different salt concentrations and a fracture width of 0,02 mm with a driving head of 30 mvp. The fracture length is here set to 35 m.

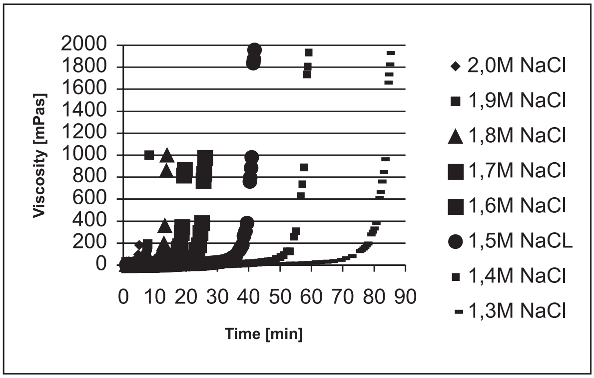


**Figure 1.** The behaviour of the viscosity development at 8°C when the silica sol is mixed with different salt concentrations of sodium chloride (NaCl) (after JANSSON, 2001)

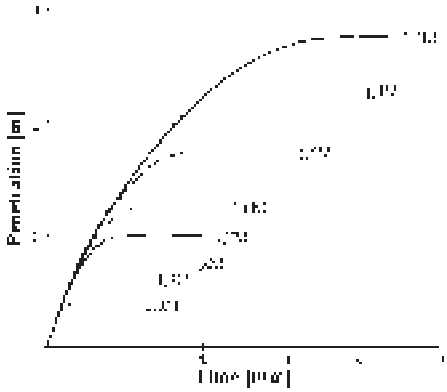

**Figure 2.** Penetration versus time for different salt concentrations with fracture aperture of 0,02 mm

## FIELD STUDY

The field study included: water pressure tests (WPT) and grouting of the rock mass. The dominant rock type in the area is a mostly middle-grained granite with features of fine-grained granite and middle-grained gneiss. The soil cover is thin in the area and approximately 6 meters of rock is above the tunnel roof. The rock wall was dry and no visible water leakage was detected. To get a view of the fractures a line mapping was made in the same height as the holes were drilled. Generally there were few fractures and the apertures appeared to be narrow.

The grout used was Meyco MP 320, which consists of two compounds, a sol of colloidal silica and a salt solution with a concentration of 10 %. In the experiment a mixing ratio of 5:1 by volume was used. The method used in the field study is called "split-spacing". First a series of boreholes were drilled and then water-loss measurement were conducted followed by grouting. Gradually boreholes were drilled between the previous holes. Grouting and WPT were conducted using a one-meter single packer.

Evaluation of the WPT, was done using Equation (2). The transmissivity of a fracture can be approximately set as the specific capacity (Fransson, 2001). This can be used to calculate the aperture of a fracture. Where: r is the density and g is the gravity.

$$\frac{Q}{dh} \approx T = \frac{\rho g b^3}{12\mu_W} \qquad (2).$$

The measured section length of each borehole is three meters. This implies that using only the results from the water loss measurements it is impossible to say whether the borehole is connected to one or more fractures. However, the fractures are narrow and the rock mass has a low permeability.

## Results and discussion

A schematic drawing of the niche where the field study took place is shown in Figure 3. The results from the water loss measurements are presented in Figure 4. Only three of the measured boreholes were permeable. The results of the calculations done with the numerical model can be seen in Table 1.

**Table 1.** Calculated penetrations with assumed penetration in the field for the three boreholes. The calculations assume one major fracture crossing the borehole

| Borehole | Fracture aperture [mm] | Calculated penetration [m] | Assumed penetration in the field [m] |
|---|---|---|---|
| 13 | 0.10 | 15.4 | *Impossible to determine* |
| 14 | 0.04 | 3.9 | 1.5-3 |
| 24 | 0.04 | 3.9 | *Impossible to determine* |

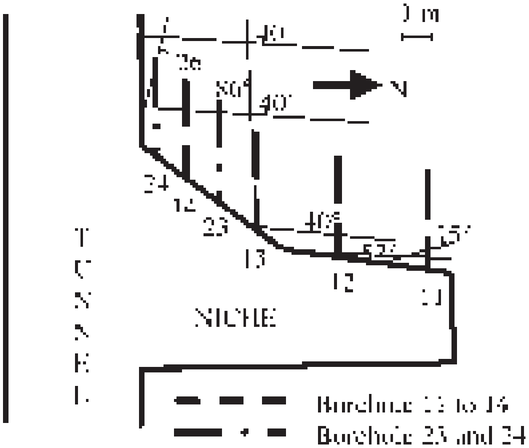


**Figure 3.** Schematic presentation of the test site. The main fractures are drawn with thinner lines showing the dip and the direction. The boreholes drilled is marked dotted thicker lines and are numbered.

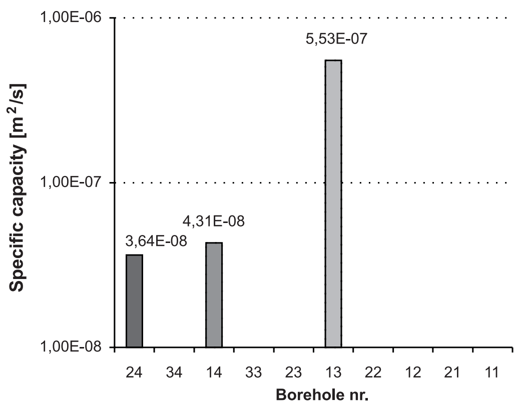


**Figure 4.** Diagram showing the evaluated result of transmissitivities from water-loss measurement in logarithmic scale. For location of the boreholes, see Figure 3.

This table compares the penetration in the three boreholes with the assumed penetrations evaluated from the field study. The fracture apertures are calculated with the assumption that the transmissivity in the borehole should be constant irrespective number of fractures. The calculated penetration if borehole 14 is connected to two fractures is 2,5 m. The schematic drawing in Figure 3 can be coupled with Figure 4 of the evaluated transmissitivities. Borehole 13 has the highest transmissitivity and hence the largest fracture aperture. Borehole 24 and 14 has approximately the same transmissitivity.
The first round of injection when borehole 14 is grouted, results in that borehole 23 is sealed and borehole 24 is still not sealed. This is probably due to the second fracture (dip of 26°) in borehole 24. The fact that there was water takes in boreholes 14 and 24 but not in borehole 34 indicates a minimum penetration of 0,75 meters (half the distance between hole 14 and 24). After the injection of borehole 14, the water-loss measurement showed that borehole 24 took water and 23 was "tight". This leads to the interpretation that the grout has penetrated at least 1,5 m, the distance between borehole 14 and 23. Since the fracture with a dip of 26° is not sealed results in a maximum possible penetration length of around 3 m. All interpretations are based upon that the apertures of the fractures are constant.

## CONCLUSIONS

Silica sol has shown a great potential to penetrate small fractures with respect to only the particle size (<50 nm). The viscosity growth shows a "hockey-stick" effect. This means that the first part of the viscosity curve has a rather constant and low viscosity while the second part shows a rapid growth in viscosity that can be described as exponential. The field study confirmed that silica sol could penetrate narrow fractures of at least an aperture of 0,04 mm. The achieved total sealing efficiency was interpreted to be 100 % due to that the intermediate boreholes were considered to be "tight". The c/c-distance was 1,5 m between the boreholes with a grouting pressure of 6 bar and a mixing ratio for the silica sol of 5:1. The gel time can be controlled with the salt concentration, which implies the advantage of a more precise grouting operation; a longer gel time results in a longer penetration. It is possible to link different permeabilities and fracture properties with specific mixing ratios of the grout. This implies that more precise design of the grouting procedure can be accomplished.

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