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Assigning Fracture Stiffness from In-Situ Deformation Measurements

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ABSTRACT:

Fracture stiffness is varying between fractures and is influenced by its proximity to a tunnel opening; if the behavior close to the opening is of interest for modelling efforts, then it may be better to use such data as input rather than high-stress laboratory measurements. A handy method for in situ testing of deformation (stiffness) and transmissivity would be beneficial to obtain data for numerical modeling of the near field of an excavation. We describe a measurement method under development that uses an anchor in a borehole and measures deformations between the anchor and the rock surface. Measurement of deformations is done during a stepwise constant head injection test providing information about both hydraulic and mechanical properties. Deformations and applied pressure is used through the effective stress concept to calculate fracture stiffness. Deformation measurements have been conducted in the TASO and TAS04 tunnels at 410 – 420 m depth at Äspö Hard Rock Laboratory (HRL), and in the Hallandsås tunnel, Sweden. Results show deformations in tested fractures 0.2 – 3 m below tunnel floor in the order of a few to tens of micrometers for injection overpressures in the order of 0.5 – 0.6 MPa. Stiffness is traditionally described as either normal stiffness or shear stiffness, the design of the experimental setup here does not allow for this distinction directly from the results; however knowledge of the orientation of tested fractures and coupling of the results to injection rates may help in discerning type of deformation.

1. INTRODUCTION

Fracture deformations are expected even at low pressure injection tests, especially close to tunnel openings where stress across fractures may be limited. Measurement of deformations can be used as an in situ method for determining fracture stiffness. Fracture stiffness is traditionally determined through high-stress testing of laboratory samples [1, 2] and the values may thereafter be used in numerical codes and Discrete Fracture Networks (DFN) models for describing in situ behavior of the fractures. We suggest that in situ measurement with a setup of basic equipment, currently under development can be used as an alternative or supplement to laboratory determination of the stiffness of individual fractures. The equipment is based on injection tests in boreholes using a special packer and an anchor.

2. MEASUREMENTS

The measurement concept is based on a mechanical anchor that is fastened at a certain depth in a borehole, from the anchor a pipe extends out of the borehole. Deformations are then measured during stepwise injection tests as movements between the anchor pipe and the rock wall. The measurement should be interpreted as the elongation of the entire tested borehole section. If the section is short and/or include a limited number of fractures, results can be interpreted as the deformation across a single fracture. Injections have been performed at constant heads 0.2, 0.4,0. 6, 0.4, 0.2 MPa above the natural pressure in the borehole sections (at depth in borehole between 0.2 and 4 m).

2.1. Equipment

The main components of the measurement equipment is 1) an anchor that can be attached to the borehole wall below a fracture of interest 2) a rod that extends from the anchor out of the borehole, and 3) a packer and injection equipment for pressurizing the rock fractures (see Fig. 1 and Fig. 2).

The first stage of development [3] was applied in the Hallandsås tunnels (Fig. 1, Fig 3) and utilized two boreholes close to each other (Fig. 1), where one was kept open with the anchor installed. The other borehole was subject to water injection.

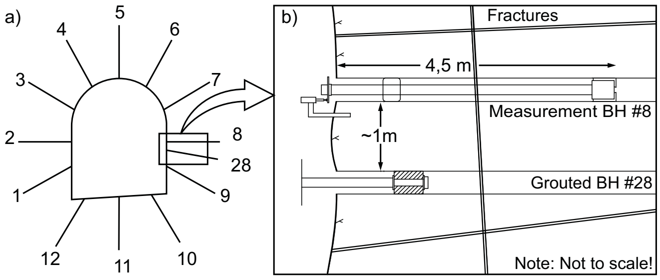

Fig. 1. Double borehole setup as adapted to the Hallandsås tunnel site.

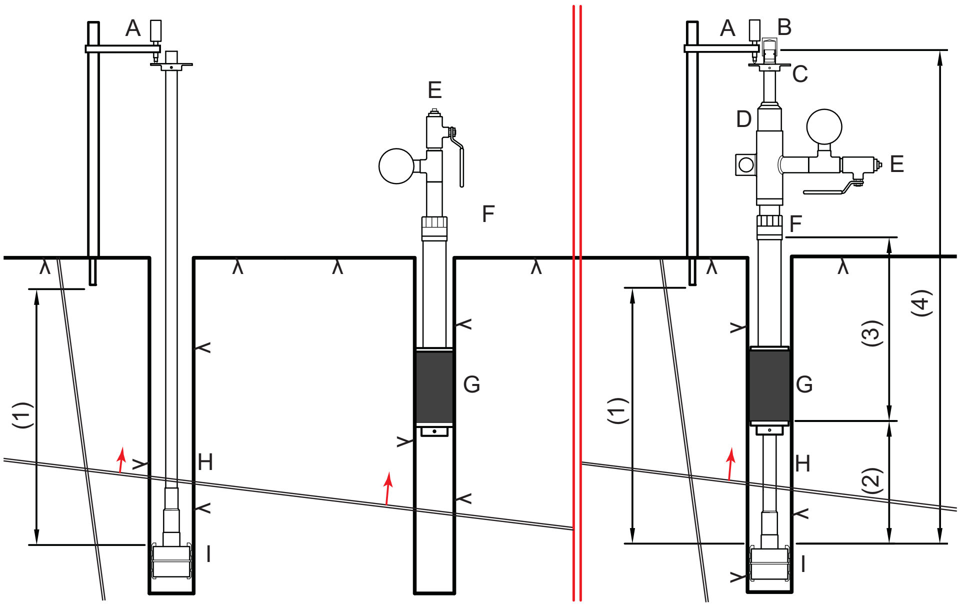

Fig. 2: **Left:** Double borehole setup. This was used in the Hallandsås and BRIE I measurement campaigns. **Right:** Single borehole setup, which was used in the BRIE II-III and the Reskontr measurement campaigns.
Measurements (1)-(4) represent: (1) interval of deformation measurement; (2) pressurized interval with deformation measurement; (3) length of packer, c 0.5-2,7 m; (4) length of deformation measurement pipe 1.1-4.6 m.
Letters A-I represent: A. deformation sensor, C. reference plane, D. seal, E. injection connection, F. packer tightening nut, G. packer rubber, H. deformation measurement pipe, I. anchor.

The second stage of development [4] included a custom packer that allowed the anchor rod to extend through the packer, hence the same borehole was used for injection and deformation measurement. Minor adjustments have been made to this setup in connection to each measurement campaign.

Common for the methods is the data acquisition principle where the anchor is placed below a fracture of interest and the rod extends out of the borehole, so that deformations are measured as the sum of deformations from the anchor to the rock wall. Data logging is made with LVDT:s and dial deformation gauges.

2.2. Measurement Procedure

The procedure for a deformation measurement with this equipment is that of a stepwise constant head injection test. First the groundwater pressure is measured in the borehole. Then the anchor and packer is installed, thereafter a stepwise injection test is conducted, where water is injected at a number of pressures relative the groundwater pressure. Such a sequence is 0.2, 0.4, 0.6, 0.4 and 0.2 MPa above the groundwater pressure. In connection with the changes from one injection step to another deformations are measured as indicated in Fig. 2, i.e. at A,C the deformations across (1) due to pressurization of (2) is measured (notations as in Fig. 2)

2.3. Calculations

Calculation of stiffness for this method is based on the concept of effective stress, in its basic form. Thus a pressurized injection of water in a fracture increase the groundwater pressure and decrease the effective stress across the fracture. In general this cause a small increase of aperture before the effective stress is zero.

Transmissivity, T, for a tested fracture is approximated as Eq. (1) [5] from the injection pump flow and pressure.

$$T \approx \frac{Q}{dh} \tag{1}$$

Other methods, such as Moye's formula, Eq. (2), may be used instead.

$$T = \frac{Q}{2 \cdot \pi \cdot \Delta h} \cdot \ln\left(\frac{L}{r_w}\right) \tag{2}$$

Rhén, I., T. Forsmark [6] found an empirical connection between storativity and transmissivity for borehole tests, Eq. (4). The Cubic Law, Eq. (3), is used to relate these tramsmissivities to apertures and deformations. Using Eq. (5) from [7] i.e. an expression that link storativity, S, and fracture stiffness, Fransson [8], [9] established an expression of stiffness from transmissivity data Eq. (6). In Eq. (5) the compressibility of water has been neglected. A hydraulic test in a borehole section that is intersected by multiple fractures is expected to reflect one of the largest and least stiff fractures [8] rather than equal parts for all intersected fractures.

The Cubic-Law hydraulic aperture, *b*, was calculated as:

$$b = \sqrt[3]{\frac{12 \cdot \mu_w \cdot T}{\rho_w \cdot g}} \tag{3}$$

where μ_w is the viscosity and ρ_w the density of water.

$$S \approx 0.0109 \cdot T^{0.71} \tag{4}$$

$$k_n^S = \frac{\rho_w \cdot g}{S} \tag{5}$$

$$k_n = \rho_f \cdot g \cdot \left(0.0109 \cdot \left(\frac{\rho_f \cdot g \cdot b_h^3}{12\mu} \right)^{0.71} \right)^{-1} \tag{6}$$

From the hydraulic aperture, *b*, Eq. (3) a hydraulic deformation for each pressure step can be calculated. The mechanical aperture, *a*, is unknown both in its initial state and during the various confining pressures. However, the change of aperture, *Δa,* relative to the beginning of the injection test is known. For each pressure step, a hydraulic and mechanical fracture normal stiffness can be calculated as the aperture change per stress change [10], this is adopted for both mechanical deformation, Eq. (7) and change of hydraulic aperture, Eq. (8). In these equations the pressure change is set to a third of the injection overpressure, thereby assuming a conical pressure profile around the injection borehole [11].

$$k_n^a = \frac{\Delta p}{\Delta a} \tag{7}$$

$$k_n^b = \frac{\Delta p}{\Delta b} \tag{8}$$

2.4. Sites

The Äspö Hard Rock Laboratory (HRL) is an underground research facility built and operated by the Swedish Nuclear Fuel and Waste Management Co (SKB). Äspö HRL has been the main site of study for the deformation measurements presented here. Measurements have been conducted on the 210-220m level in tunnels TASO and TAS04, see Fig. 3.

The main rock type at both tunnels at Äspö HRL is Äspö diorite (a quartz monzodiorite) with occurences of fine grained granite. The major horizontal rock stress is generally perpendicular to the mid-atlantic ridge and in the range of 15-25 MPa, while the minor horizontal and vertical stresses is in the range of 10-15 MPa [12].

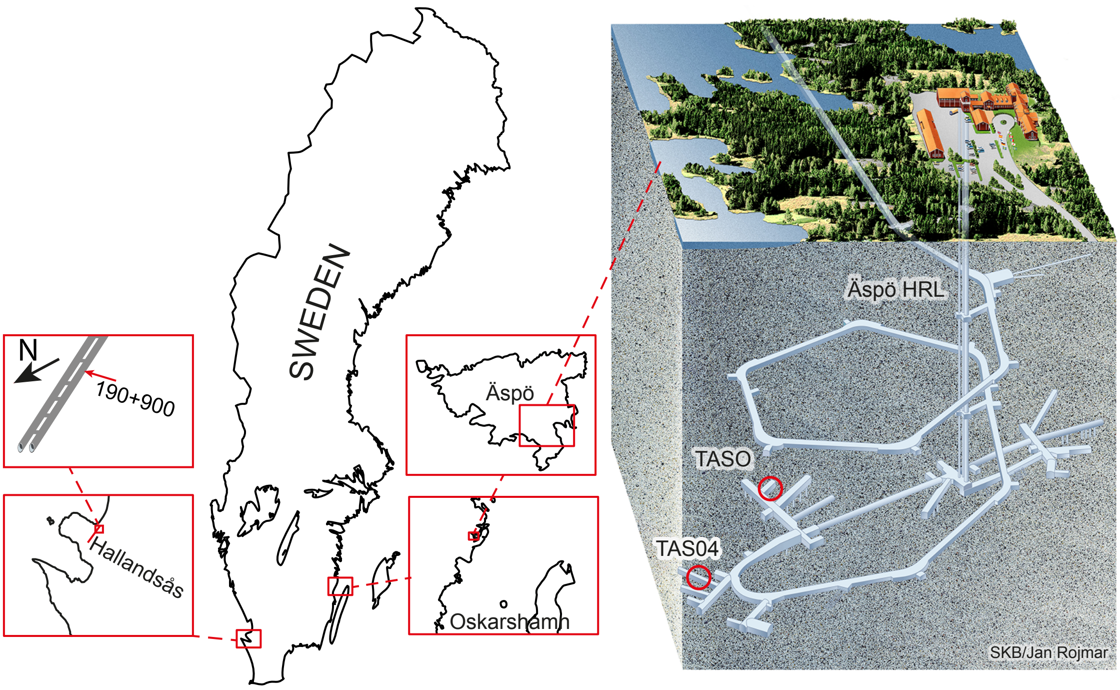

Fig. 3: Left: The location of the Hallandsås tunnel test site. Right: The location of Äspö Island and Äspö HRL, as well as the test sites TASO and TAS04 in the HRL.

The Hallandsås site is situated in a heavily fractured gneiss horst with dolerite and amphibolite dikes. Principal rock stresses is varying, but estimated from a rule-of-thumb to 2-4 MPa. The measurement boreholes is situated between the two tunnel pipes (radius ≈ 5 m) [13].

3. SETUPS AND RESULTS

The equipment is, as mentioned before, under development. So far it has been used for five measurement campaigns briefly described below.

3.1. Hallandsås

The first attempt was performed with the double borehole setup during post grouting in the Hallandsås tunnels (low stress, wide apertures). Four measurements were made during water pressure tests (WPT) and three during grouting.

Deformations of up to 200 µm were registered but 30 – 50 µm was most common. Corresponding stiffness is around 10 GPa/m, but some values up to 80 GPa/m were also calculated. Hydraulic apertures for injection was around 200-300 µm with injection pressures of about 1 MPa.

3.2. BRIE I (TASO)

The double borehole setup was used during characterization of the TASO tunnel, within the BRIE experiment Äspö HRL [14]. One borehole was instrumented with the deformation anchor (KO0014G01) and two nearby boreholes, on either side of a deformation zone were subject to the injection (KO00**17**G01, KO00**15**G01). #17 had groundwater pressure of 1.0 MPa, and injection rate corresponding to b=10 µm. #15 had no groundwater pressure, and hydraulic aperture, b = 130 µm.

The first test showed no deformation. The second showed deformations of 3 µm, corresponding to stiffness of 40 GPa/m.

3.3. BRIE II (TASO)

A prototype of the single borehole setup was used in the TASO tunnel, Äspö HRL. This was the first attempt with single borehole setup and experienced some difficulties with deformations in the equipment itself. Six measurements were conductede in three boreholes (same as before, #14, #15 and #17).

Due to these difficulties fair statements can be given for two measurements: A fracture at 0.4 m depth in borehole KO0014G01 did deform a couple of microns (groundwater pressure during this test was 0.01 MPa, b = 15 µm). Indications of small deformation were also seen in a test 3 m below tunnel floor in borehole #17 was also registered. Groundwater pressure before this test was 0.19 MPa, and injection rate corresponding to b = - 10 µm.

3.4. BRIE III (TASO)

This campaign involved the single borehole setup, with issues identified in the previous campaign resolved. Six measurements were made in four boreholes (KO0014G01, KO0015G01, KO0016G01, KO0017G03) still at the BRIE site, TASO tunnel, Äspö HRL. The results improved with respect to previously identified issues, but a new one arose. All tests got significant positive readings when the highest pressure is released. This raised the question of deformation modes and initiated further assessment of the equipment.

3.5. Reskontr (TAS04)

Single borehole setup at a new site, the TAS04 tunnel, Äspö HRL. Nine measurements were conducted in five 1 m deep boreholes. The anchor was placed near the bottom of the holes and packer at 0.2 and 0.6m below floor.

During stepwise injections of 50, 250, 500, 250, 50 kPa deformations of up to about 50 µm was measured. Most commonly the deformations were in the range of 0-20 µm. Hydraulic apertures, *b*, were most commonly 15-30 µm but for the test with largest deformations *b* was around 50-70 µm. Corresponding stiffness is below 40 GPa/m for some of the evaluated injection steps, but values above a measurement limit of 100 GPa/m is more common (this limit correspond to deformations less than 1 µm).

4. DISCUSSION

4.1. Equipment and Reliability

The double borehole setup seemed robust in its measurements, but has the disadvantage of an open, freely flowing measurement borehole. The single hole setup solved this issue, but had some initial issues, all of which are not fully resolved. For the fifth measurement campaign the stability was promising. In this case the boreholes were short (1 m). For longer boreholes, > 2.5 m, to anchor it is probably better to use a double-anchor configuration where the anchors are linked across a fracture, rather than from below a fracture to tunnel wall beside the borehole. There are double anchor systems available on the market.

In general the least stiff fractures are the ones of greatest engineering importance, a low stiffness in the applied

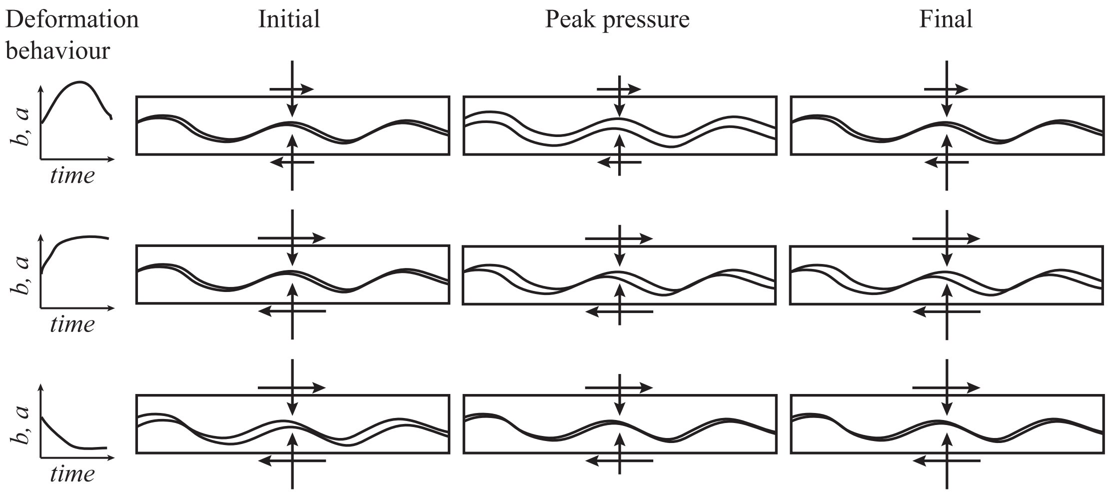

Fig. 4: Three types of test deformation behavior described with sketches (simplified to the loading and unloading of one step). The first row represents resilient deformation as normal opening and closure. Middle and last row describe two cases of shearing resulting in positive and negative permanent deformation. Note that these are conceptual sketches and neither aperture scale nor force arrows are to scale.

range of injection pressures correspond to deformations of tens of micrometers.

4.2. Deformation mode

The deformation behavior of the different tests should be put in relation to different possible deformation modes (see Fig. 4). Normal deformations can be expected to be resilient and positive with increasing pressure (unless crushing or flushing of debris occur), a type of deformation that is rarely seen in the measurement results. Permanent deformations are expected when shearing of the rough fractures occur. Depending on multiple factors in the fracture surface position/matedness, increased as well as decreased aperture may be the result of a pressure load in the fracture.

4.3. Evaluation Method

Assuming a conical pressure profile and taking average pressure as a third is a conceptual simplification as is the chain of equations used.

4.4. Implications for DFN:s

For sparsely fractured rock mass, as is the case at Äspö HRL it is possible to test individual fractures with this setup. Together with thorough characterization of boreholes it is possible to design and execute a deformation measurement campaign that provides near-tunnel stiffness data for individual fracture sets. Such information would help in designing DFNs that not only include fracture-set specific properties, but also reflect local changes due to excavation.

5. CONCLUSIONS

This paper relates to the conceptualization and parameterization around fracture deformations and fracture stiffness.

The stiffness in the Excavation Damage Zone, i.e. close to a tunnel opening represent a rock volume with a changed stress field compared to surrounding rock. Movements in fractures due to excavation is expected, as well as the formation of new blast (induced) fractures. Therefore the EDZ rock volume needs to be treated differently from the unaffected surrounding rock mass in terms of stiffness properties.

The measurement and evaluation methodology presented here make use of simultaneously collected hydro- and mechanical data that with a common interpretation is able to capture the order of magnitude of small deformations and corresponding fracture stiffness in the vicinity of tunnels.

6. ACKNOWLEDGMENTS

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