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Estimation of deformation and stiffness of fractures close to tunnels using data from single-hole hydraulic testing and grouting

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ABSTRACT

Sealing of tunnels in fractured rocks is commonly performed by pre- or post-excavation grouting. The grouting boreholes are frequently drilled close to the tunnel wall, an area where rock stresses can be low and fractures can more easily open up during grout pressurization. In this paper we suggest that data from hydraulic testing and grouting can be used to identify grout-induced fracture opening, to estimate fracture stiffness of such fractures, and to evaluate its impact on the grout performance. A conceptual model and a method are presented for estimating fracture stiffness. The method is demonstrated using grouting data from four pre-excavation grouting boreholes at a shallow tunnel (50 m) in Nygård, Sweden, and two post-excavation grouting boreholes at a deep tunnel (450 m) in Äspö HRL, Sweden. The estimated stiffness of intersecting fractures for the boreholes at the shallow Nygård tunnel are low (2–5 GPa/m) and in agreement with literature data from field experiments at other fractured rock sites. Higher stiffness was obtained for the deeper tunnel boreholes at Äspö which is reasonable considering that generally higher rock stresses are expected at greater depths. Our method of identifying and evaluating the properties and impact of deforming fractures might be most applicable when grouting takes place in boreholes adjacent to the tunnel wall, where local stresses might be low and where deforming (opening) fractures may take most of the grout.

1. Introduction

When constructing tunnels below the groundwater level, sealing of water-conducting features is necessary to decrease the water inflow and limit the influence on the groundwater level. Lowering of the groundwater level may result in settlements and damage to buildings, particularly in areas were the soil cover consists of clay. Sealing of tunnels is commonly performed by pre- or post-excavation grouting. In the case of pre-excavation grouting, boreholes are drilled in the tunnel front to intersect fractures to be sealed (Fig. 1a), whereas in the case of post-excavation grouting the boreholes are drilled following excavation into the walls of the tunnel (Fig. 1b). Consequently, all boreholes are found close to the tunnel wall, an area where rock stresses can be low and both rock stresses and groundwater pressure change within small distances. Considering this and the relationship between normal stress, σ_n, fluid pressure, p, and effective normal stress, σ'_n:

$$\sigma'_n = \sigma_n - p \tag{1}$$

the grouting pressure (fluid pressure) used when grouting can result in deformation due to hydromechanical coupling.

Indications of hydromechanical effects during grouting have been identified e.g. at Botniabanan in Sweden [1], where a change in grouting pressure resulted in a larger than expected increase in grout flow. During a grouting experiment at Äspö Hard Rock Laboratory (Äspö HRL) at 450 m depth fracture deformation was indicated by the sound of the rock when closing the packer of a borehole. Evans et al. [2] comment that for fractures that are verging on shear failure at the prevailing stress conditions, shear displacement can occur for a small pressure increase. The importance of the in-situ stress is also discussed by Beitnes in a study of the post-excavation grouting at Romeriksporten, Norway [3]. According to the author, a low stress in any direction increases the difficulty to obtain a good grouting result. Some consider high pressure grouting helpful and suggest this approach to achieve low tunnel inflows (e.g. [4]). However, there is a risk that grout penetrates the large aperture fractures which may open up and close parallel fractures effectively reducing grout penetration into smaller fractures. Thus, high pressure grouting may not necessarily be the solution for a general sealing of small aperture fractures. Guglielmi et al. [5] describe investigations of a superficial carbonate rock (30 m × 30 m × 15 m) that is an unconfined

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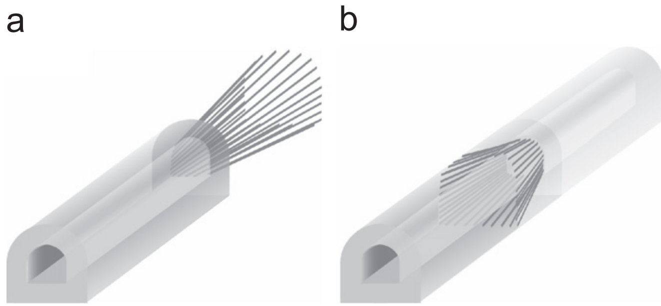

Fig. 1. (a) Pre-excavation grouting with grouting boreholes drilled in tunnel front and (b) post-excavation grouting with boreholes drilled in the tunnel wall. During hydraulic testing and grouting fracture deformation may occur due to redistribution of stresses or the tunnel being found at shallow depth.

aquifer drained by a natural spring. Modeling performed shows that in case of parallel fractures, opening of a tested fracture induces a closing (poroelastic) of the surrounding parallel fractures. In addition, analysis related to the same site [6] considers faults intersected by bedding-planes where a high inelastic deformation magnitude at bedding-planes resulted from sliding induced by normal closing of the tested faults. In this case, damage related to the deformation explains the bedding-plane permeability increase. In addition, as commented by the authors [5], reducing the effective normal stress leads to a normal opening and reduced shear strength and during fracture shear movements aperture can change due to dilation. Deformation of fractures is likely to increase the amount of grout flowing into the tunnel (particularly for post-excavation grouting) and if not sealed, opening of the grouted and/or adjacent fractures could result in a decreased tightness of the tunnel.

Field methods for estimate of deformation and stiffness of fractures are discussed in, e.g. [5,7–10]. In [5] a method referred to as the High-Pulse Poroelasticity Protocol (HPPP) is introduced that uses a probe with fiber-optic sensors that allows high-frequency measurements. In [7] another type of mechanical borehole device is used to evaluate fracture stiffness and storativity. In [8] an approach is presented in which a fracture was pressurized at five different pressure steps and the transmissivity distribution within the fracture was evaluated from hydraulic tests in a number of boreholes for the different pressure steps. Further, in [9] two-pressure injection tests and multiple-pressure injection tests were performed and analyses were made using coupled hydromechanical finite element simulations (ROCMAS). In [10] an effort to characterize normal stiffness and hydraulic conductivity of a major shear zone in granite at Whiteshell site in Canada is described.

Gustafson and Stille [11], on the other hand, suggested that grouting data can be used to estimate flow dimension and here we propose that flow dimension and deformation are closely linked under certain conditions. An open fracture with few points of contact and no fracture filling (a higher flow dimension) is more likely to deform compared to a fracture with a large amount of contact points (a lower flow dimension), and therefore it is important to identify these features. The present paper takes this approach with the objective of developing a method by which data from hydraulic testing and grouting can be used to identify deforming fractures, estimate fracture stiffness and indicate low effective stress close to a tunnel. This can then serve as a tool to better adapt the grouting design and improve its performance.

In this paper, a conceptual model and a method are presented for estimating fracture normal stiffness. The local stresses may be unknown but we recognize that a low stiffness generally indicate a low effective stress. The method is demonstrated using grouting data from four pre-excavation grouting boreholes at a shallow tunnel (50 m) in Nygård, Sweden, and two post-excavation grouting boreholes at a deep tunnel (450 m) in Äspö HRL, Sweden. For the shallow Nygård tunnel the stresses are expected to be low and some boreholes with a flow dimension between two (2D) and three (3D) where identified and investigated. A 3D-flow could be a direct indication of deformation. As a comparison, the two boreholes from the deep Äspö HRL are investigated, here higher stresses are expected but deformation can occur also at this depth. The data used here are often available from normal grouting applications and since grouting is made along the tunnel this would provide valuable information that could be used for modification of grouting design and possibly also for reinforcement design.

2. Method

2.1. Flow dimension

The flow dimension is considered important. For a two dimensional flow, few points of contact within the fracture and a low fracture stiffness are expected. During grouting, grouting pressure, p_g, grouted volume or grout take, V, flow of grout, Q, and time, t, are documented. These pVt-data can be used to identify flow dimension using the following expression [11]:

$$\frac{d\log V}{d\log t}=\frac{d\ln V}{d\ln t}=\frac{dV}{V}\frac{t}{dt}=\frac{dV}{dt}\frac{t}{V}=\frac{Qt}{V} \tag{2}$$

According to Gustafson and Stille [11], a slope of $d\log V/d\log t\approx 0.8$ indicates a radial (2D) grout spread, and a slope of $d\log V/d\log t\approx 0.45$ implies a 1D flow system. The general idea is that fractures with a flow dimension smaller than two are expected to be less influenced by hydromechanical coupling. If the flow dimension is larger than two, this could be a direct sign of fracture deformation.

2.2. Conceptual model: Estimate of fracture stiffness

The fracture normal deformation is expressed as

$$\Delta u_n=\frac{\Delta\sigma'_n}{k_n}=\frac{\Delta\sigma_n-\Delta p}{k_n} \tag{3}$$

where $\Delta\sigma'_n$ is change in the effective normal stress, $\Delta\sigma_n$ is the change in total normal stress, Δp, is the fluid pressure change and k_n is the fracture normal stiffness. Although the normal deformation is generally non-linear when normal stress is applied, it may be approximated by a linear function of effective stress over an incremental displacement Δu_n. The rate of deformation is greatest at low values of normal stress [12].

When a fracture is filled with grout under pressure, a deformation may occur (Fig. 2). A change in pressure results in a fracture volume change, ΔV, and the hypothesis is that this can be used to estimate fracture stiffness. At a certain time, t, the integral of the fluid pressure change, referred to as $\AA$ [13], has resulted in a deformation giving a larger fracture aperture. The mean (arithmetic) aperture of a deformed fracture, b_{adef}, is therefore assumed to consist of the initial aperture, b_{0a} that will be estimated using hydraulic tests, and a deformation due to grouting, Δb_a:

$$b_{adef}=\Delta b_a+b_{0a} \tag{4}$$

The principal idea is that the aperture, b_{adef} resulting from grout-induced fracture opening can be estimated based on a penetration length, I, and a grout take measured in the field, $V_{field,t}$