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Technical Note

A new apparatus and methodology for hydromechanical testing and geometry scanning of a rock fracture under low normal stress

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1. Introduction

Fractures conduct most of the groundwater in hard crystalline rock. The ability of each fracture to transmit water depends on the void space between the fracture surfaces. The geometry of these surfaces is the result of the current stress situation, the manner in which the fracture was formed and subsequent movements, stresses and infillings. This results in a system that is difficult to describe in a way that is both hydraulically and mechanically sound. Such descriptions are useful though, for example in multiphysics modelling for advanced underground constructions, such as repositories for underground storage of nuclear waste.

The cubic law[1] represents the fracture surfaces as two smooth parallel plates without any contact, which is useful for describing the flow of water through the fracture.[2] However, the cubic law is not sufficient to describe the interaction of stresses across the fracture as this would require an understanding of the roughness of, and contact between the surfaces. Key aspects of a fracture that will be accounted for in this work is the hydraulic aperture of the fracture, b and number of contact points and contact area. The aperture being related to the pore volume and the ability of the fracture to transmit water and the contacts being related to the transference of stresses.

The aim of the work presented here was to develop an experimental method and the necessary equipment to produce a coupled hydromechanical and surface geometry description of fracture samples with the intention to capture aperture and distance between contact points, here suggested to be approximated by its correlation length. The correlation length is assumed to give an indication of the distance between contact points and to give further insight into the aspect ratio of the voids (i.e. contact point distance divided by aperture). The laboratory experiment also aimed at investigating the validity of the aperture–stiffness relationship derived from the basic model in[3] and the related field data analyses and assumptions: a fracture of low compressive stress across, and limited prior deformation. Focus in this experiment is on fracture normal deformation rather than shear.

A situation with low confining stresses can be expected at shallow depths in bedrock but also at certain locations and in certain directions in the vicinity of an underground opening, where the stress situation is disturbed by the opening. In most cases, previous work involving hydromechanical laboratory experiments on rock cores did not aim at describing the situation in an excavation damage zone (EDZ) close to an underground opening with the presence of stress redistributions and loosened rock.

Tatone and Grasselli[4] presented a method for scanning the geometry of the fracture surfaces and their interrelationship and hence the void geometry of fractures. We present a similar fracture void scanning method, but with samples under predetermined compressive stress. This is an extension of the setup and procedure we used for previous hydromechanical experiments on the same core samples, which included hydraulic testing and deformation measurements across the fracture in the samples.[5]

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The working hypothesis was that a carefully designed surface scanning procedure allows the fracture void geometry to be mapped, enabling a comparison to be made between the calculation of the hydraulic apertures in the samples using cubic law and a geometry-based hydraulic aperture calculation, such as the one presented by Zimmerman and Bodvarsson.[6] Experimental testing of the agreement between the previously suggested stiffness to hydraulic aperture relationship[3,7] and the results from this experiment is conducted on the assumption that the results would fall into line with the stiffness to hydraulic aperture relationship in Refs. 3,7. With this comparison both in situ and laboratory scale is included, but apart from that the issue of upscaling is left for coming studies.

Three samples were scanned and analysed in this study. The samples were core drilled from slabs sawn from tunnel walls at the Äspö Hard Rock Laboratory, Oskarshamn, Sweden. The samples have undergone permeameter testing[8] and a subsequent re-run using updated equipment and focus on hydromechanical testing.[5]

2. Theory

2.1. Fracture apertures

A common understanding of the flow in fractures is that it can be compared to the flow between two smooth parallel plates: the cubic law.[1] The applicability to rock fractures has been investigated and in general the description holds good for smooth, wide aperture fractures with low flow rates.[2] The cubic law includes the hydraulic aperture b [μm], the transmissivity of the fracture T [m^2/s], the viscosity μ_w [Pa s], the density of water ρ_w [kg/m^3] and the acceleration due to gravity g [m/s^2]:

$$b = \sqrt[3]{\frac{12\mu_w T}{\rho_w g}} \tag{1}$$

A more general description of hydraulic aperture and its relationship to the mechanical aperture and surface appearance has been sought empirically[9] and analytically.[6] Zimmerman and Bodvarsson[6] present a relationship that involves the hydraulic aperture b [μm], the arithmetic mean of the mechanical aperture a [μm], its standard deviation σ [μm] and the proportion of contact area of the surfaces c [dimensionless]:

$$b^3 = \langle a\rangle^3\left[1 - \frac{1.5\sigma_a^2}{\langle a\rangle^2}\right](1 - 2c) \tag{2}$$

For larger values of standard deviation the expression within square brackets in Eq. (2) becomes negative and the result unrealistic. An alternative expression that handles large standard deviations better is[10,11]:

$$b^3 = \langle a\rangle^3\left[1 + \frac{\sigma_a^2}{\langle a\rangle^2}\right]^{-3/2} \tag{3}$$

If the fracture aperture distribution is lognormal, as was found in Refs. 12–15, the geometric mean of the aperture is a very good approximation of the hydraulic aperture.[16] However, describing the data by means of a statistical distribution does not capture the void space entirely. Hakami and Larsson[17] include the spatial variation by conducting a variogram analysis, thus establishing a correlation length of the aperture variation.

An empirical relationship using data from hydraulic interference tests, including data from the same area as the samples in this study,[18] links the transmissivity and storativity of fractures:

$$S = 0.0109T^{0.71} \tag{4}$$

A link between fracture stiffness and storativity[19] is achieved as once the negligible influence of the compressibility of water is removed from the expression:

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

Together with the cubic law, Eq. (1), linking transmissivity and aperture, an estimate of fracture stiffness from an in situ hydraulic test is reached which depends on the properties of the injected water (density, viscosity), gravity and the hydraulic aperture of the fracture. This relationship is assumed to capture the fracture that is least stiff and most transmissive in a tested interval:

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

In Ref. 3, a basic conceptual model of fracture contact distances resulted in a link between stiffness and aperture on the form

$$k_n \approx Cb^{-2} \tag{7}$$

Both Eqs. (6) and (7) include estimates of fracture stiffness being inversely proportional to hydraulic aperture squared, b^{-2}, but achieved from hydraulic and geometrical concepts, respectively:

2.2. Measurement of fracture aperture

Surface geometry and/or aperture have been studied for a long time, with different approaches used for the measurement and under different boundary conditions. Tatone and Grasselli[4] provide an account of methods published over four decades.

When the surface geometry of a fracture is measured, a common definition of aperture is the difference in the z-coordinate when a best-fit plane of the fracture is aligned with the x–y plane (Eq. (1)).[4,11,20] This is used because of its computational simplicity but results in overestimated apertures, especially for rough surfaces[21]:

$$a(x, y) = z_2(x, y) - z_1(x, y) \tag{8}$$

Methods that attempt to measure the fracture aperture include rubber injection into a fracture sample with subsequent measurement of rubber thickness by photographing the cast with a light source underneath.[22] In this case, the position between the fracture sides was established by placing one half on top of the other, with the stress across the fracture resulting from the weight of the overlying part. Other injection approaches has been utilised in e.g. Refs. 13,14 with the possibility of determining the aperture under specific stress across the fracture, but with impractical and/or low resolution aperture data acquisition, through slicing the sample and digitising the cross sections.

Laser profilometry scanning of fracture surfaces with stereo-photographic data collection was used in Ref. 21 where the aperture, under the stress resulting from the weight of the overlying sample part. Here the aperture was determined by means of referenced data collection with spheres on the sample halves.

Another recent approach to optical profilometry with white light used a special jig to fit the sample halves.[20] This approach helped to determine accurately how each surface characterisation could be combined to obtain an aperture but it did not allow for measuring the aperture situation under stress.

The method in Ref. 4 included measurement using an optical measurement system named ATOS, which was used on a fractured rock core sample by first establishing the spatial interrelationship between the core pieces and then scanning the fracture surfaces. When using this method, the core pieces were placed in a best-fit position and clamped before determining their relative positions and surface geometry measurement. The clamping stress was however unknown.