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Effect of shear displacement on the hydraulic conductivity of a fracture

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ABSTRACT

The effect of shear displacement inclined relative to macroscopic water flow on the hydraulic conductivity of a rock fracture was estimated, using synthetic fractures that reproduce a tensile fracture in granite. The results showed that the hydraulic aperture normalized by the mean aperture increased with the angle between the directions of shear displacement and macroscopic water flow, according to a sinusoidal function of twice the angle. Formulae were established to estimate the hydraulic aperture of the fracture as a function of the mean aperture, the standard deviation of the initial aperture, the shear displacement, and the angle between the shear displacement and macroscopic water flow, based on results obtained in both this work and previous work, but neglecting scale effects. By assuming the mechanical properties of the fracture based on experimental results for granite, but neglecting scale effects, the hydraulic conductivity of the fracture with an arbitrary direction under a given state of stress (σ_1=29 MPa, σ_2=25 MPa and σ_3=13.5 MPa) was estimated for macroscopic water flow in the directions of both σ_1 and σ_2. When the contour map of the transmissivity of the fracture is plotted on a stereonet of the normal direction of the fracture in the principal axes of stress, there is a ridge (line of the local maximum) of transmissivity in the circumferential direction, and the inclination angle of the ridge from the σ_3-axis decreases with shear displacement, since shear dilation increases with both a decrease in normal stress and an increase in shear displacement. Furthermore, for the condition of stress given in this study, the transmissivity for macroscopic water flow in the direction of σ_1 is maximum for a fracture with a normal direction within the σ_2–σ_3 plane, while that in the direction of σ_2 is maximum for a fracture with a normal direction within the σ_1–σ_3 plane.

1. Introduction

The hydraulic properties of fractured reservoirs, such as for geothermal energy extraction and natural gas/oil production, are governed by the properties of the fractures that provide the main conduits for fluid flow. Evaluation of the hydraulic properties of a fracture system is also important for designing rock structures, such as for the underground storage of energy and underground disposal of high-level radioactive wastes. Thus, many experimental and analytical studies have focused on the hydro-mechanical properties of fractures [1,2], and previous studies have revealed several major points. As for the mechanical properties of a fracture, it has been shown that the normal stress versus closure curve of a fracture is highly non-linear, and this non-linearity increases with a decrease in the matedness of the fracture [3–8]; the shear stiffness increases with normal stress [9–12]; the dilation angle decreases with shear displacement due to the breakage of asperities during shear; and shear dilation is suppressed by an increase in normal stress until contraction eventually occurs under large normal stresses [9–14]. For the hydraulic properties of a fracture, it has been shown that the hydraulic conductivity of a sheared fracture is much greater than that of a normally closed fracture due to shear dilation [12–17]; the hydraulic aperture relative to the mean aperture is mainly governed by the mean aperture relative to the standard deviation (SD) of the initial aperture (the aperture of a fracture that is in contact at a single point) [18–24]; and a sheared fracture is hydraulically anisotropic, with a higher conductivity in the direction perpendicular to the shear displacement than parallel to the shear displacement [13,15,17,24–28]. Moreover, it was also shown that there are scale effects regarding the mechanical and hydraulic properties of a fracture, although such effects may disappear when the size of a fracture exceeds a certain value according to the shear displacement [8,9–11,23,24,27,29,30]. Thus, many factors affect the hydraulic conductivity of a fracture under stress.

In previous studies, anisotropic water flow in a sheared fracture has mostly been investigated only for macroscopic water flow parallel to or perpendicular to the shear displacement. However, in general, a fracture is oriented in an arbitrary direction

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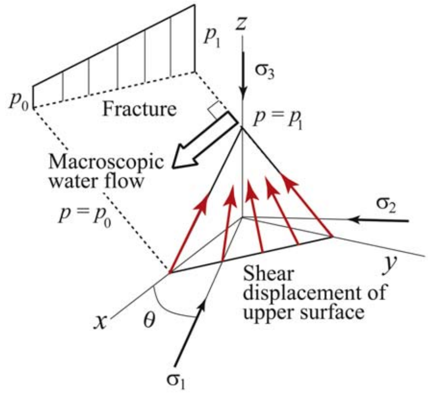

Fig. 1. Direction of shear displacement in a fracture in comparison with that of macroscopic water flow.

with respect to the in situ stress, and the mechanical behavior (closure and shear displacement) of a fracture vary with the orientation of the fracture. Accordingly, since the direction of macroscopic water flow is given by the hydrogeological conditions, the shear displacement of a fracture is not always exactly parallel to or perpendicular to the direction of macroscopic water flow. Fig. 1 illustrates that the direction of shear displacement in a fracture varies according to the directions of the principal stresses, and, as a result, the shear displacement is inclined relative to the direction of macroscopic water flow with a given direction. Thus, to evaluate the hydraulic conductivity of a fracture with an arbitrary direction with respect to in situ stress, we need to estimate the effect of shear displacement that is inclined relative to macroscopic water flow.

In this study, by using synthetic fractures that were created on a computer by a spectral synthesis method [24] to reproduce the ratio of the power spectral density (PSD) of the initial aperture to that of the surface height, as determined for a tensile fracture of 1 m in Inada granite [32], we estimated the effect of shear displacement inclined relative to macroscopic water flow by 0–90° on the hydraulic aperture of the fracture. Shear displacements of 12.5, 25 and 50 mm were applied to fractures of 0.2, 0.4 and 0.8 m in size, and the hydraulic aperture relative to the mean aperture during closure was determined by solving Reynolds equation with a finite difference method. Next, by using the results obtained above as well as those obtained in a previous study for synthetic fractures of from 0.2 to 6.4 m [24], the hydraulic aperture of the fracture was formulated as a function of the mean aperture, the SD of the initial aperture, the shear displacement and the angle between the directions of shear displacement and macroscopic water flow; scale effects were ignored to simplify the problem. Finally, by assuming the mechanical properties of the fracture based on experimental data on tensile fractures in Inada granite and ignoring scale effects, the hydraulic conductivity of a fracture with an arbitrary direction relative to stress was estimated for a given state of stress as an example, and the effects of the stress and hydraulic anisotropy of the fracture on the variation in hydraulic conductivity with the normal direction of the fracture were discussed.

2. Methods

2.1. Method for creating a sheared fracture

Synthetic fractures with isotropic surfaces were created by a spectral method based on fractional Brownian motion (fBm) [33]. We will briefly describe the method below; details can be found in [24]. In this method, a fractal surface is created by the inverse Fourier transform of the Fourier components. The amplitudes of the Fourier components are the same for two surfaces of a fracture and given so that the scaling law of the SD (σ_h) of the surface height along a linear profile for a fracture with a size of L, given by the following equation, may be satisfied:

$$\sigma_h = \sigma_{h0}(L/L_0)^{3-D}, \tag{1}$$

where σ_{h0} is the SD of the surface height for a fracture with a reference size L_0, and D is the fractal dimension of the surface ($2 < D < 3$). In this study, we used the following values [32]: D=2.297, σ_{h0}=1.966 mm, and L_0=0.2 m. The phases of the Fourier components for one of the surfaces (upper surface) are given by $2\pi R_1$, where R_1 is a series of random numbers uniformly distributed from 0 to 1. To give a gradual increase in the matedness between the two surfaces for wavelengths greater than the so-called mismatch length scale, we introduced phases for the lower surface that differ from that for the upper surface by $2\pi\gamma(f)R_2$, where R_2 is another series of random numbers and the function $\gamma(f)$ is given so that the ratio between the PSDs of the surface height and the initial aperture, obtained theoretically, may satisfy a given value for spatial frequencies f smaller than the inverse of the mismatch length scale (0.568 mm). We used the values measured in [32] for the ratio of the PSDs.

Three square fractures with sizes of 0.4, 0.8 and 1.6 m were created by the method described above using a grid spacing of about 0.2 mm to reproduce the SD of the initial aperture along a linear profile with an error of $< 0.4\%$. The grid points for both the x- and y-directions were 2048, 4096 and 8192 for fracture sizes of 0.4, 0.8 and 1.6 m, respectively. As shown in Fig. 2, shear displacements (δ_s) of 12.5, 25 and 50 mm in the direction with an angle θ_d from the x-axis were applied to the upper surface of a fracture, which was then allowed to contact the lower surface at a single point to determine the initial aperture distribution. The initial aperture was determined for half of the fracture size due to the offset caused by shear displacement. We refer to half of the original side length as the fracture size (L). Hence, the sheared fracture created in this study measured 0.2, 0.4 and 0.8 m. The upper surface was further lowered to give closure from the initial state in steps of about 1 mm. During closure of the fracture, the aperture of the overlapped area was simply set to zero. Thus, we avoided breaking asperities during shear deformation. Therefore, we neglect the effect of debris produced by shearing on the hydraulic conductivity of the fracture.

In reality, the surfaces of a fracture would be more or less damaged when the fracture is sheared under normal stress, and this damage becomes greater as the normal stress increases, depending on the strength properties of the rock. Accordingly, the aperture distribution would more or less deviate from that we

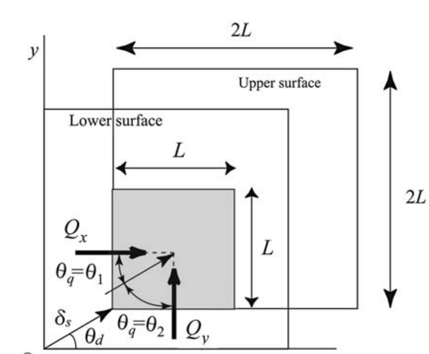

Fig. 2. Direction of shear displacement (δ_s) and the angle (θ_q) between the directions of shear displacement and macroscopic water flow (Q_x and Q_y).