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The variation of fracture aperture and permeability during normal closure and shearing and with scale in large synthetic fractures

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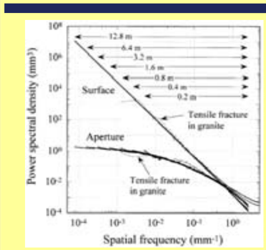
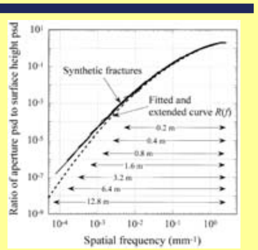
INTRODUCTION

Synthetic fractures of various different scales from 0.2 m to 12.8 m were created using the Glover *et al.* spectral method. All the synthetic fractures were normalised such that the ratio of the power spectral density of the initial aperture (i.e., the aperture when the surfaces are in contact at a single point) to that of the surface height was the same as that determined for a tensile fracture of 1.0 m size. First, the size effect on the standard deviation of the initial aperture was analyzed for fractures with and without shearing. Next, by taking aperture data at constant intervals to establish a flow area, water flow was simulated for fractures during both normal closure and closure after shearing, by solving Reynolds equation to determine the hydraulic aperture. When the fracture is closed without shearing and has the same mean aperture, the effect of the fracture size on the hydraulic aperture disappears if the fracture is larger than about 0.2 m, since beyond this size the standard deviation of the initial aperture is almost independent of the fracture size. When the fracture is closed after shearing, the hydraulic conductivity shows remarkable anisotropy, which becomes more significant with both shear displacement and closure. However, the relation between the hydraulic aperture normalized by the mean aperture and the mean aperture normalized by the standard deviation of the initial aperture is almost independent of both the fracture size and shear displacement when the shear displacement is less than about 3.1% of the fracture size, at which point the standard deviation of the initial aperture of the sheared fracture is almost independent of the fracture size.

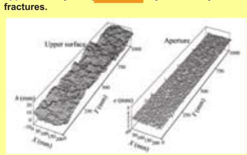
SURFACE AND APERTURE MODELLING



The average PSD of the heights of the two surfaces and that of the initial aperture for all synthetic fractures in comparison with those for the tensile fracture in granite (thin lines). The range of the spatial frequency is shown for each fracture size. The measured PSDs of the surface height and the initial aperture of the tensile fracture were approximately reproduced by the synthetic fractures.



The ratio of the PSDs of the initial aperture and the surface height, with a curve of $R(f)$ for reference. The ratio for the synthetic fractures is only slightly greater than $R(f)$ on the log–log plot. Thus, the method for creating a synthetic fracture proposed in this study has been proved to be useful for creating a realistic fracture with a desired degree of mated-ness.



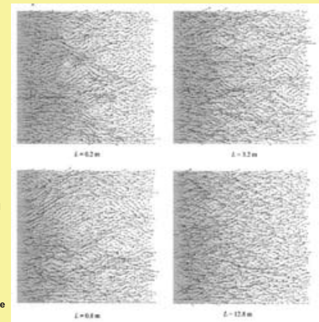
Upper surface and initial Aperture of a tensile fracture With a size of 1 m x 0.2 m.

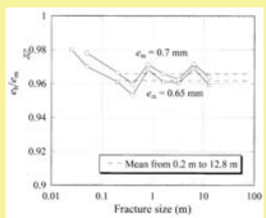
PERMEABILTY DURING NORMAL CLOSURE

Velocity and pressure fields were calculated by solving Reynold`s equation for fracture sizes L of 0.2, 0.8, 3.2 and 12.8 m when they are closed to have a mean aperture e_m of 0.65 mm. Linear equations derived from the finite difference form of the Reynolds equation were constructed by removing points in contact where the aperture is zero and accordingly the pressure cannot be defined, and the pressure distribution was solved by the Gauss–Seidel method.

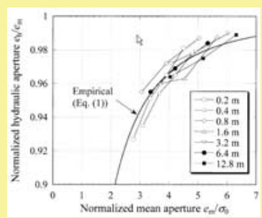
The pressure is shown using a gray scale, where pressure decreases with brightness. The small white area indicates the area in contact, where the pressure cannot be defined. The data used for the velocity field represent only about 2.3% of those obtained at all grid points. Note that the same value for the macroscopic pressure gradient was used for all fractures so that a similar velocity could be obtained for fractures of various sizes.

The flow is more or less tortuous for all fracture sizes, but no appreciable difference is observed among them. This is because the aperture distribution relative to the fracture size is similar for all fracture sizes.





Fracture size effect on the normalised hydraulic aperture e_h/e_m when the fracture is normally closed to have a mean aperture of 0.65 and 0.7 mm.



Relation between e_h/e_m and e_h/σ_o obtained for synthetic fractures without shearing in comparison with the equation below.

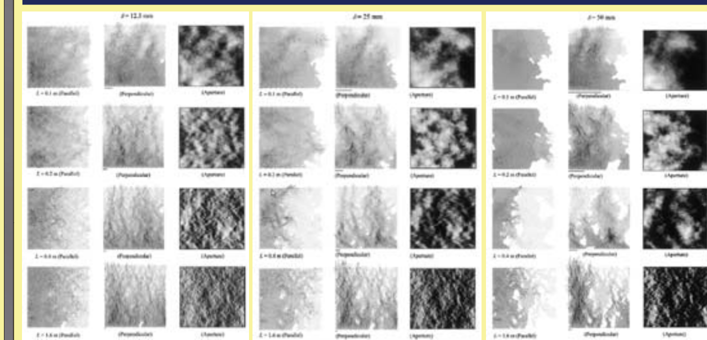
$$\frac{e_h}{e_m} = \sqrt[3]{1 - \frac{1.13}{1 + 0.191(2(e_m/\sigma_0))^{1.93}}}$$

Matsuki *et al.* (1999) proposed the above equation as a size-independent formula for estimating the normalized hydraulic aperture e_h/e_m of a hydraulic fracture with a size of less than 16 mm as a function of the mean aperture normalized by the SD of the initial aperture e_m/σ_o. The relation between e_h/e_m and e_m/σ_o, obtained in this study, is summarized in the diagram above right . Although the relations obtained in this study for large fractures were scattered around the curve of the equation, the mean relation can be given by the equation. Accordingly, we can use the equation to estimate the permeability of a large fracture if the mean aperture and the SD of the initial aperture are determined.

CONCLUSIONS

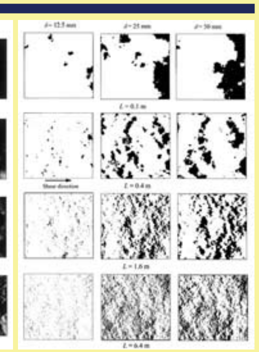
1. The spectral method proposed in this study for creating a synthetic fracture approximately reproduced the ratio of the PSD of the initial aperture to that of the surface height, determined for a tensile fracture of 1 m.
2. When the fracture is closed without shearing to the same mean aperture, the fracture size effect on the hydraulic aperture disappears when the fracture size exceeds about 0.2 m, since beyond this size the standard deviation of the initial aperture is almost independent of the fracture size. An empirical formula was proposed to estimate the hydraulic aperture of a fracture of any size by giving the mean aperture and the standard deviation of the initial aperture.
3. When the fracture is closed after shearing, the hydraulic conductivity shows remarkable anisotropy. The hydraulic aperture in the macroscopic flow perpendicular to the shear displacement is much greater than that in the macroscopic flow parallel to the shear displacement. This anisotropy increases with the shear displacement when the fracture is closed to have the same mean aperture.
4. The relation between the hydraulic aperture normalized by the mean aperture and the mean aperture normalized by the standard deviation of the initial aperture is approximately independent of both the fracture size and shear displacement when the shear displacement is less than about 3.1% of the fracture size, where the standard deviation of the initial aperture of the sheared fracture is almost independent of the fracture size.

FLOW AND PRESSURE FIELDS DURING SHEAR



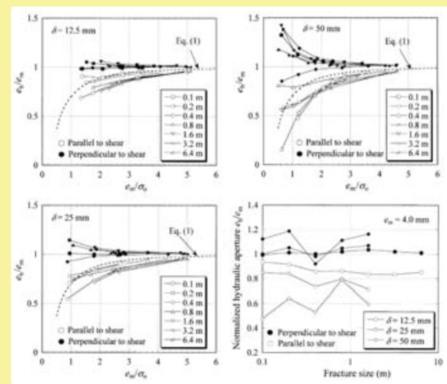
The velocity and pressure fields for the two directions of macroscopic flow and the aperture distribution when fractures of 0.1, 0.2, 0.4 and 1.6 m in size are sheared by 12.5, 25 and 50 mm, respectively, and closed to have a mean aperture of 4.0 mm. The scale beneath the middle figures indicates the magnitude of the shear displacement for reference. The contour maps of the aperture distribution are given at every 1 mm, and brighter parts indicate areas with a greater aperture.

Clearly, channeling flow develops in the macroscopic flow perpendicular to the shear displacement, although it is also observed in the macroscopic flow parallel to the shear displacement. The flow is more localized as the shear displacement increases or as the fracture size decreases. Furthermore, the number of channels tends to increase with the fracture size and decrease with the shear displacement for fractures that are equal to or smaller than 1.6 m



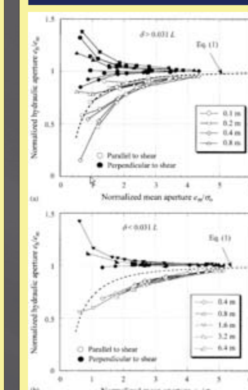
The figure shows areas where the aperture is smaller than 1.0 mm in black for all shear displacements, when fractures of 0.1, 0.4, 1.6 and 6.4 m are closed to have a mean aperture of 4.0 mm. We call an area that forms an isolated island a ridge. The ridges contain points in contact and water flows through channels that may form between ridges. The figure clearly shows that ridges and channels form approximately perpendicular to the shear displacement. Thus, the ridges inhibit the macroscopic flow parallel to the shear displacement and at the same time channeling flow develops in the macroscopic flow perpendicular to the shear displacement.

HYDRAULIC APERTURE DURING SHEAR

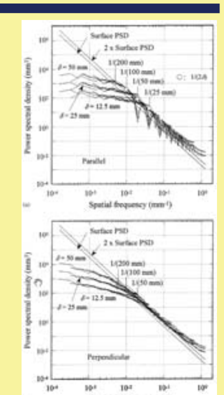


The effect of the fracture size on the normalized hydraulic aperture e_h/e_m when the fracture is sheared by δ = 12.5, 25 and 50 mm and is closed to have a mean aperture e_m of 4.0 mm. Solid symbols indicate the normalized hydraulic aperture for macroscopic flow perpendicular to the shear displacement and open symbols indicate that parallel to the shear displacement.

MECHANICAL APERTURE DURING SHEAR



The relation between e_h/e_m and e_m/σ_o for (a) δ>0.031L and (b) δ<0.031L. When δ>0.031L (9 of 21 cases), the relations are scattered due to the dependence on the shear displacement relative to the fracture size (δ/L=0.06–0.5). However, when <0.031L (12 cases), the scatter is greatly reduced and similar relations are obtained.



The ensemble-averaged PSDs of the linear profiles of the initial aperture for all synthetic fractures when the fracture is sheared by 12.5, 25 and 50 mm in the shear direction and perpendicular to the shear direction. The PSD of the surface height together with that multiplied by two are also shown for comparison.

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