Experimental and Numerical Analysis of Hydrothermal Channel Flow Through a Tensile Fracture in Granite

N. Watanabe[1] and N. Tsuchiya[1]

[1]Gradate School of Environmental Studies, Tohoku University, Sendai 980-8579, Japan

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ABSTRACT

In crystalline rocks, fracture networks control fluid flow (i.e. rock permeability). Inhomogeneous distribution of fracture aperture width due to natural fracture topology may produce inhomogeneous fluid flow (channel flow). Hydrothermal experiments for a tensile fracture in granite indicate that the effect of aperture width distribution and any inhomogeneity is pronounced. Numerical simulation for 2-D fluid flow through a facture shows that inhomogeneity of fluid flow may be enhanced, and promote fluid channels within the rock.

Introduction

Modeling fluid flow in fractured rock has been extensively studied, to predict production rates of petroleum, natural gas and geothermal fluids. In crystalline intrusions, rock matrix permeability is small compared to fracture permeability, so fracture networks may be regarded to control fluid flow (in terms of permeability). A fracture is ideally defined as two smooth and parallel surfaces, separated by a constant aperture width. Inhomogeneous aperture width distribution, however, due to roughness and contact points on the natural fracture surface may produce inhomogeneous fluid flow (i.e. channel flow; Brown, 1987; Judith, 2002).

The purposes of this study are to investigate the relationship between fluid-rock interaction and channel flow, and to model dynamic changes of fluid velocity due to change of aperture width. Hydrothermal flow in granite, containing a single (mode I) tensile fracture was studied, with a numerical model proposed on the basis of the experimental results.

Hydrothermal Flow Experiment

Rock Sample And Experimental Apparatus

A hydrothermal flow experiment was performed on an Iidate Granite block sample, containing a single (mode I) tensile fracture. The length of the granite block is 290 mm, width is 170 mm, and height is 30 mm (Figure 1).

Fluid flow through the fracture is parallel to the y-axis shown in Figure 1, at constant flow rate under pre-determined temperature and pressure conditions. The rock sample is set inside a sample holder coupled with a seal block, made of stainless steel (Figure 2, overleaf). Fluid is pure water. A pre-heater was installed to heat up starting solution before injecting into the seal block.

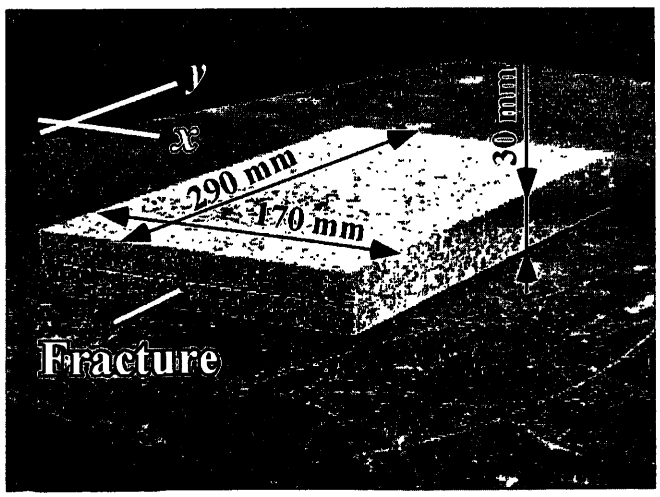

Figure 1. Fractured granite "slab" sample.

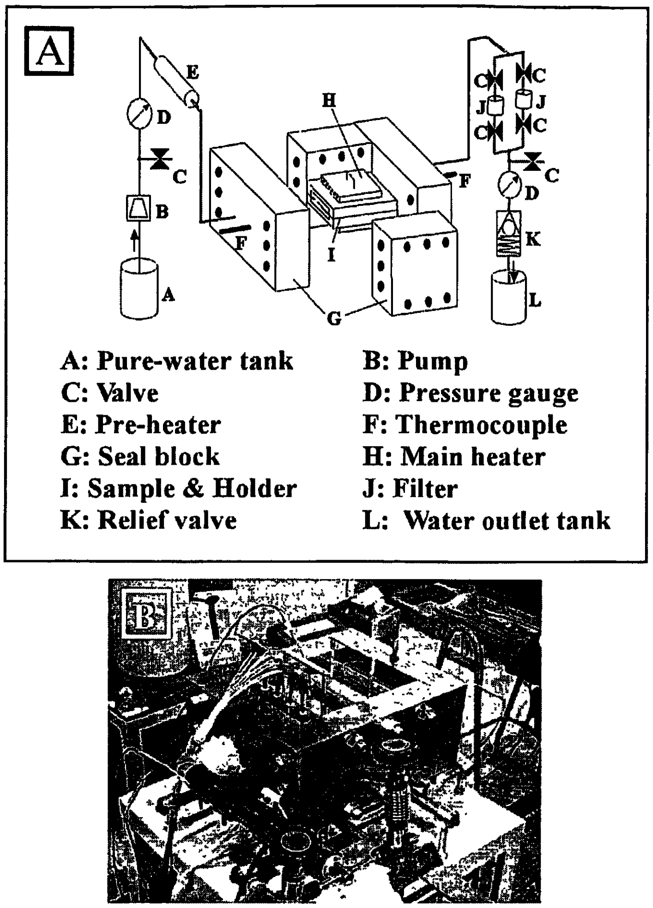

Figure 2. (A) Schematic model of experimental apparatus; (B) Photograph of seal block.

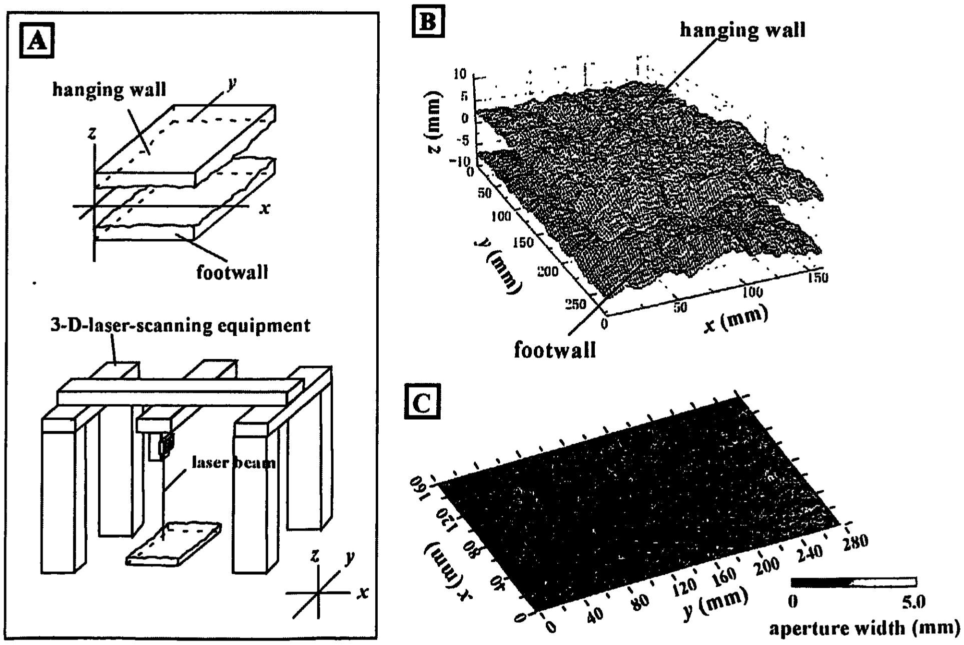

Figure 3. Procedure to infer aperture (fracture) width distribution. (A) Fracture surfaces of hanging wall and footwall are analyzed using 3-D laser scanning equipment; (B) Asperity height (z-axis) is obtained for a given x-y point; (C) Distribution of aperture width, for a given x-y point, is based on at least one point contact between fracture surfaces.

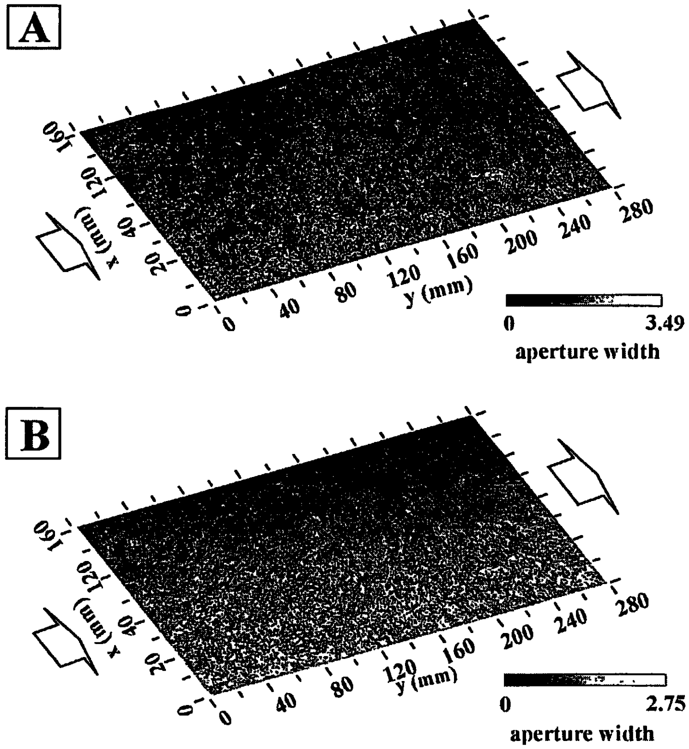

Figure 4. Distribution of aperture width, (A) before, and (B) after experiment. Arrows indicate flow direction through the fracture.

Fracture Surface Mapping

The hanging wall and footwall of the fracture are separated, and the fracture surface is measured using 3-D laser scanning equipment. The laser beam scans the fracture surface with constant x-y steps of 0.5mm (Figure 3A). Asperity height (z-axis) is obtained for each point (Figure 3B). Accuracy of positioning for the equipment is 1μm for *x-y* position and 3μm for *z* direction. Digital data sets of (*x*, *y*, *z*) are obtained for both sides of the fracture. "Aperture width of fracture" is defined by distance between corresponding *x-y* positions on both sides of the fracture, with at least one point of the fracture surface hypothetically in contact (Figure 3C).

Experimental results

We performed an experiment under temperature, hydraulic pressure, flow rate and duration conditions of 140°C, 1MPa, 1.0ml/min and 720 hours respectively. Figure 4 shows the aperture width distributions, normalized using the arithmetic mean value of calculated aperture width, before and after the experiment. A comparison of the two maps in Figure 4 reveal that the large aperture width area evident before the experiment was larger after the experiment, whilst the small aperture width area detected before the experiment was still small after the experiment. The arithmetic mean value, a_m, and the standard deviation, σ_a, of aperture width indicated a_m = 1.39 mm and σ_a = 0.449 mm before the experiment, and a_m = 1.93 mm and σ_a = 0.738 mm after the experiment. The value of σ_a/a_m, which represents the degree of inhomogeneity of aperture width distribution increased from 0.359 to 0.382. Consequently, the experimental result indicates a changed aperture width distribution and pronounced aperture width distribution inhomogeneity.

Mathematical Model For Hydrothermal Flow

In order to simulate 2-D fluid flow through a facture, the following mathematical model was proposed. Assumptions for the model are:

- Fluid is incompressible.
- Influences of viscosity change and gravity are neglected.
- Fluid flow obeys Darcy's law.
- The cubic law gives local permeability.

Equation of continuity representing mass balance in the system is described as:

$$\frac{\partial}{\partial x}\left(a \cdot k\frac{\partial p}{\partial x}\right)+\frac{\partial}{\partial y}\left(a \cdot k\frac{\partial p}{\partial y}\right)=0 \quad (1)$$

where a is aperture width, k is permeability and p is hydraulic pressure. As we assume permeability follows the cubic law, the permeability is given by

$$k=\frac{a^2}{12} . \quad (2)$$

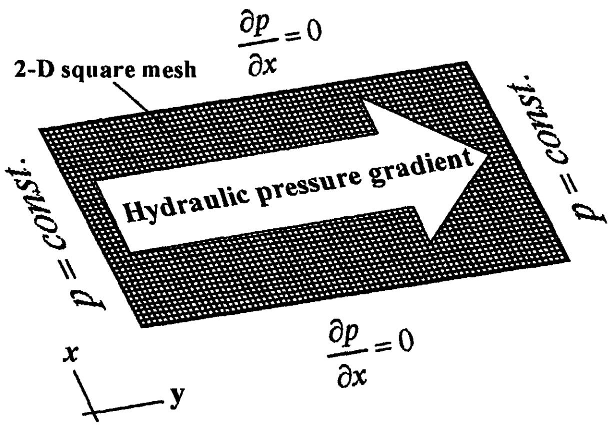

Figure 5. Modeling of fracture and boundary conditions for finite difference method.

A fracture is modeled by 2-D square mesh and Eq. (1) is numerically calculated by the finite difference method under adequate boundary conditions shown in Figure 5. So, we can calculate the flow velocity by Darcy's law:

$$u=-\frac{k}{\mu}\frac{\partial p}{\partial x} , \quad (3)$$

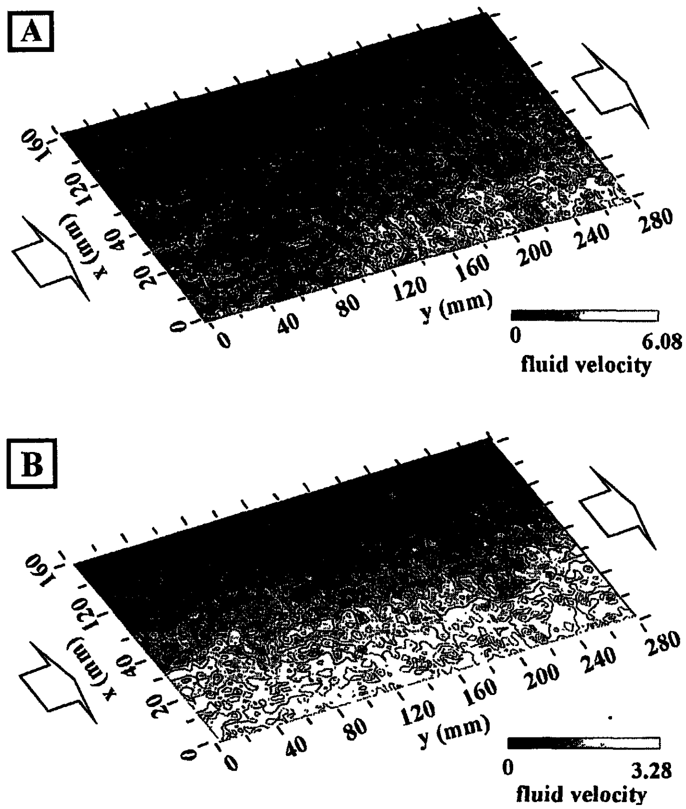

Figure 6. Distribution of fluid velocity, with flow direction indicated by arrows: (A) initial fluid velocity corresponds to aperture width distribution shown in Figure 4A; (B) indicates fluid velocity after hydrothermal experiment.

$$v=-\frac{k}{\mu}\frac{\partial p}{\partial y} , \quad (4)$$

where u and v are flow velocity in the direction of x and y respectively, μ is fluid viscosity.

Figure 6 shows the fluid velocity distributions, which correspond closely with the aperture width maps shown in Figure 4. The original aperture width maps consists of 321 × 561 points, however, numerical calculation was performed for 41 × 71 points due to calculation time. The calculated fluid velocity was normalized by the arithmetic mean value of the fluid velocity on each map. A comparison of fluid velocity maps before and after the experiment show that fluid flow inhomogeneity was enhanced, and that fluid channel was created in the rock.

Numerical Model for Aperture Width Change During Fluid Flow

According to experimental results and fluid flow numerical calculations, channel flow occurred in a natural fracture. We carried out the hydrothermal experiment at constant temperature and pressure, so the primary reason of the channel flow is best explained by influence of fluid velocity as defined by the local aperture width of the fracture. Water-rock interaction, involving various dissolution and precipitation reactions, is also an important factor that may characterize the channel flow. Dissolution and precipitation processes consist of complex chemical and transport steps at the interface between rock and fluid. Dissolution and precipitation rates differ for individual rock-forming minerals and transport phenomena in the boundary layer, at the rock-fluid interface, has a great effect on water-rock interactions (Hara and Tsuchiya, *in press*). The channel flow process is difficult to model, but we used a fundamental equation (Eq. 5) to describe aperture width change, which incorporates the following assumptions:

- Rate of aperture width change is characterized by mean fluid velocity (at a given point location).
- Mean fluid velocity is defined as square root of fluid velocity in x and y direction.

$$\frac{\partial a}{\partial t} = \alpha\left(\sqrt{u^2+v^2}\right)^{\beta} , \qquad (5)$$

where a is aperture width, t is time, u and v are fluid velocity in the x and y direction respectively. α and β are constants. The change in aperture width due to fluid flow may be inferred using the hydrothermal fluid flow model, with:

- Distribution of fluid velocity was based on measured aperture width, as an initial condition.
- Change rate of aperture width is calculated by Eq. (5). Localized change of aperture width is obtained, which lead to an estimation of fluid velocity.

Here, we infer α and β to be unity, and change of aperture width can be calculated. The distribution of aperture width shown in Figure 4A was used as initial condition.

Figure 7 shows the change in aperture width distribution and fluid flow. Figures 7A-1 and 7B-1 show the initial distribution of aperture width and fluid velocity, and Figures 7A-2 and 7B-2 show the final distribution of aperture width and fluid velocity, with σ_a/a_m 1.2 times larger than the initial condition. Aperture width and fluid velocity are normalized by the arithmetic mean value in each map. Inhomogeneity of fluid flow was enhanced, and consistent with changes in aperture width distribution shown in Figures 4 and 6.

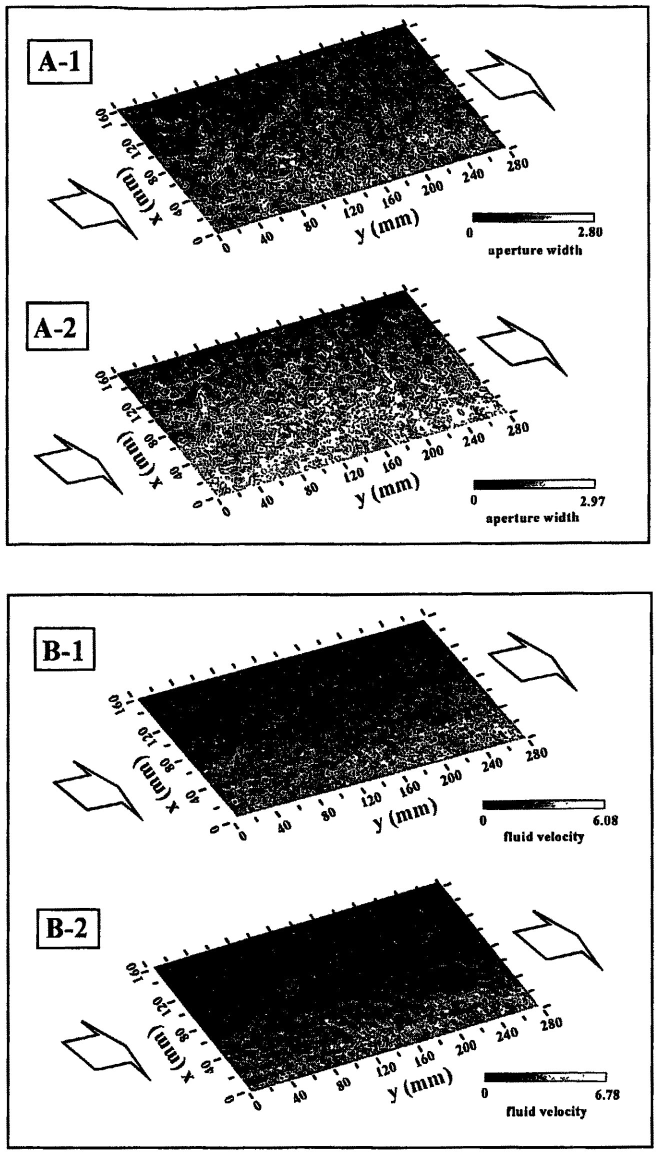

Figure 7. Change of aperture width distribution and fluid flow, with flow direction indicated by arrows: (A-1) initial distribution of aperture width; (A-2) final distribution of aperture width; (B-1) initial distribution of fluid velocity; (B-2) final distribution of fluid velocity.

Conclusions

Mapping of fracture surfaces in granite, generated by tensile cracking, was performed to characterize 2-D (hydrothermal) fluid flow through the fracture. Natural rock fracture surfaces are rough and the distribution of aperture width is spatially inhomogeneous. A 2-D mathematical model describes fluid flow through the fracture, and effect of inhomogeneity on aperture width distribution, which concurs with experimental results. Channel flow through the fracture is affected by chemical and transport behavior and inhomogeneous aperture width distribution. Further study is required to develop a broad mathematical model that effectively describes 2-D (hydrothermal) fluid flow in fractures.

Reference

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