Evaluation of Hydromechanical Behavior of Rock Joints

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1. Background and Introduction

In recent years, the management of radioactive waste becomes an important environmental issue in all countries operating nuclear power plants. Geological disposal is the most promising option for a safe long-term management of radioactive waste as agreed by scientists and politicians, which requires the understanding of the physical, mechanical and hydraulic properties of the proposed host rocks. In this study, the shear-flow coupling tests of rock joints are carried out under different boundary conditions based on a newly developed shear-flow test apparatus. The shear behavior as well as the transmissivity of the rock joints is estimated. The Finite element method (FEM) is used to simulate the flow in the rock joints. By comparing the numerical simulation results to the experimental data, several important parameters and relations about hydromechanical behavior of rock joints are proposed.

2. Experimental apparatus and methodology

A high performance hydromechanical test apparatus is developed in this study. This apparatus supports the shearing process under both Constant normal load (CNL) and Constant normal stiffness (CNS) boundary conditions with the hydraulic tests at the same time. When the upper specimen is changed into a transparent replica, the flowing image in the rock joint can be monitored with a CCD camera placed above the upper replica after trace flow is injected into the joint. By analyzing the flow images, it could help us to find out some detailed information of the hydraulic behavior of rock joints.

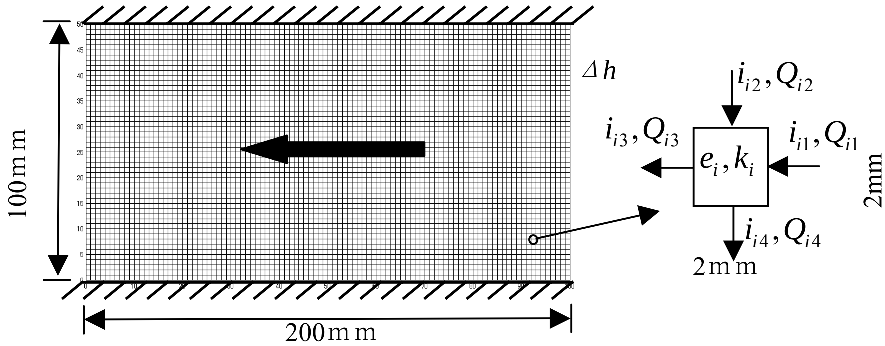


Figure 1. Model for FEM analysis.

In this study, shear-flow coupling experiments are carried out under various boundary conditions. The weight of drained water is measured during experiment. Then, the flow rate and conductivity of a rock joint could be obtained based on Darcy's law and the so-called "cubic law" as follows.

$$Q = Aki = we\frac{ge^2}{12\nu}i \qquad (1)$$

where Q is the volumetric flow per unit area A, i is the gradient, k is the hydraulic conductivity, g is the acceleration due to gravity, e is the hydraulic aperture, ν is the kinematic viscosity of the fluid and w is the breadth of the flowing zone between the parallel plates.

Based on the measured flow velocity, the hydraulic aperture e could be calculated by Equation (1), and then be used to compare with the mechanical aperture during shearing, by which, the relationship between hydraulic aperture and mechanical aperture could be obtained.

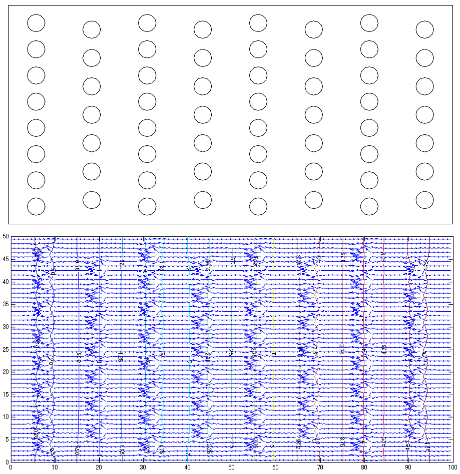


Figure 2. One example of the arrangement of contact area (15%) and flow vector analysis.

3. Numerical simulations

Assuming the following geometric and kinematic conditions: 1) the fractures consists of two smooth parallel plates with uniform aperture, 2) the fluid is incompressible and fluid flow is laminar in the steady state, the governing equation for fluid flow in a single fracture is derived from the mass conservation equation and Darcy's law as follows:

$$\frac{\partial}{\partial x}\left(T_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(T_{yy}\frac{\partial h}{\partial y}\right)+Q=0 \qquad (2)$$

where Q is an initial source and sink taken to be positive when fluid is slowing into and negative when flowing out of the fracture, and T_{xx} and T_{yy} are called the fracture transmissivity in x and y- directions respectively, defined by "cubic law" expressed as following equation:

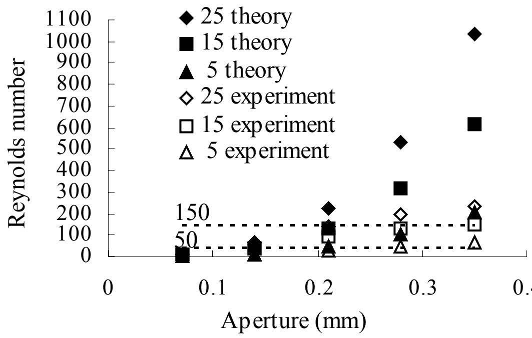


Figure 3. Comparison of the Reynolds number from Darcy's law and experimental results. 25, 15 and 5 are hydraulic gradients.

$$T_{xx} = T_{yy} = T(x, y) = \frac{\rho g e^3}{12\mu} \tag{3}$$

where ρ is the fluid density, μ is dynamic viscosity.

The FEM code developed in this study uses linear quadrilateral elements to solve the equations mentioned above. The fracture was divided into 5000 (100×50) small square elements of size 2 mm, and then the aperture of each element was given from measured values, as shown in Figure 1.

4. Experimental and simulation results and discussions

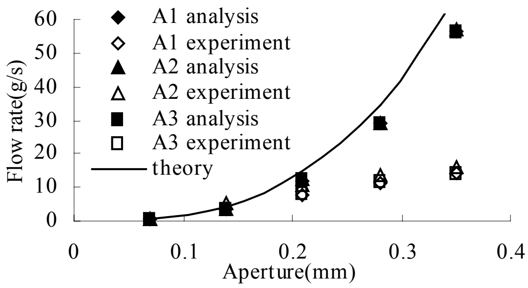
Before doing experiment on the natural rock joints, we carried out a number of hydraulic experiments to acquire some basic parameters for numerical simulation. During researching the surface damage of rock joints in shearing, we found that after peak shear stress, the contact ratio of the two faces of joints decrease rapidly and generally exhibits a relatively low value (depending on the dilation property of rock joints, around 10%~40%). Based on this, we designed 9 patterns (contact ratios 15%(A), 20%(B), 25%(C), each one with 3 different distribution patterns respectively, one example is shown in Figure 2) of contact areas on two smooth parallel plates with uniform aperture, and injected water with hydraulic gradients of 5, 15 and 25, respectively, to evaluate the influence of contact area on the water flow.

The Reynolds numbers for each cases were calculated based on both Darcy' law and experimental results (Figure 3 shows the results for contact ratio of 15%). The theoretical results exhibit much higher values than the experimental results as the Reynolds numbers increase. Combining Figure 3 and 4, it could be found that in the low flow rate phase, these two results agree well with each other. After this (i.e. the Reynolds number is larger than 200), deviation of them increases gradually, during which, the turbulent flow component is believed to have happened. It is considered that only the Reynolds number is larger than an experiential value (i.e. 2000) that the laminar flow could start to change to turbulent flow. However, our experiments show that this change may happen under a very low Reynolds number depending on the structure of the fracture. Therefore, we suggest that only depending on Reynolds number is not enough to judge a flow is laminar or turbulent, the inner structure of aperture could also have a dramatic influence on this change. The results also show that different arrangements of contact regions with the same contact ratio have small influence on the water flow and the flow rate drops under larger contact ratio.

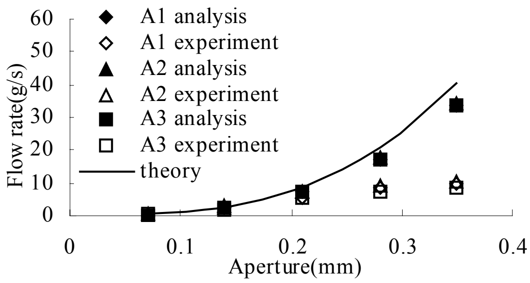
We calculated the hydraulic aperture from the experimental data and compared them with the measured mechanical aperture to evaluate their relationship. The regression analysis shows that the hydraulic aperture and mechanical aperture satisfies the following relation:

$$e = R \cdot E^N \tag{4}$$

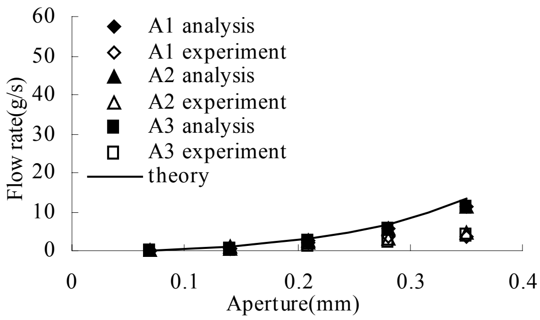
where e is the hydraulic aperture, E is the mechanical aperture, R is a parameter depending on the surface roughness of joint wall, N is nearly a constant but influenced by the level of aperture and hydraulic gradient. In the situation of our experiment, we suggest that N is around 0.5 in the phase that turbulent flow has happened. Modified aperture is shown in Figure 5.



(a) Hydraulic gradient 25.



(b) Hydraulic gradient 15.



(c) Hydraulic gradient 5.

Figure 4. Comparison of the flow rate from experiment and numerical analysis with contact ratio 15%.

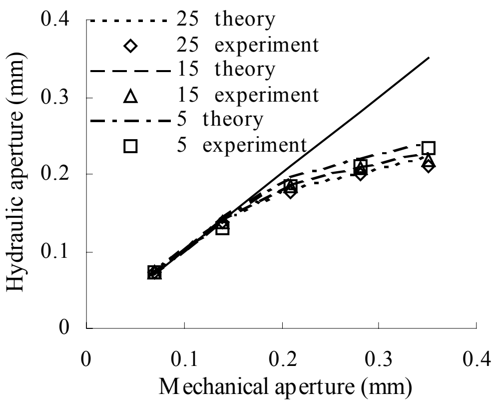


Figure 5. Modified hydraulic aperture by Equation (4). 25,15 and 5 are hydraulic gradients.

5. Conclusions

In this study, a high performance hydromechanical apparatus was developed to evaluate the combined hydraulic and mechanical behavior of rock joints. We suggest that the inner structure of joint (roughness, contact ratio, etc.) have large influence on the flow state. A correlation between hydraulic aperture and mechanical aperture is proposed, which will be used in numerical simulation to analysis the hydromechanical behavior of natural rock joints.

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