Thesis summary

COUPLED SHEAR-FLOW PROPERTIES OF ROCK FRACTURES

Graduate School of Science and Technology
Nagasaki University, Japan

Bo LI
Abstract:

In rock engineering, two issues have been considered significantly important in the development of underground spaces in rock masses: (1) the shear behaviour of rock fracture is the key factor that controls the mechanical behaviours of fractured rock mass encountering a rock structure construction; (2) water flow, mostly taking place in rock fractures, can alter the mechanical and hydrogeological properties of rock mass, affecting the stability of rock structure, especially facilitating the particle transport through rock fractures. The interactions of them can be investigated by coupled shear-flow tests in laboratory, as a basic building block to the assessment of the performance of underground rock structures such as radioactive waste repositories.

In this thesis, the shear behaviour and coupled shear-flow behaviour of rock fractures were investigated through laboratory experiments by using direct shear test apparatus and coupled shear-flow-tracer test apparatus, respectively. Constant Normal Load (CNL) condition as well as a more representative boundary condition for underground rock-Constant Normal Stiffness (CNS) condition were applied to these shear tests on the rock fracture samples with various surface characteristics to evaluate the boundary condition sensitivity and the influences of surface characteristics of rock fractures on their shear-flow behaviours. Numerical simulations on the coupled shear-flow tests using FEM were carried out using a special algorithm for treating the contact areas as zero-aperture elements and their results were compared with experimental results. Visualization technique was introduced into the coupled shear-flow tests by using CCD camera to capture the flow images in a fracture with the use of transparent upper halve and plaster lower halve of fracture specimens. Image processing was then applied to these flow images to obtain digitized aperture distributions, combining which with numerical simulations, the evolutions of contact area, aperture and transmissivity of rock fracture during shear process were estimated. Coupled shear-flow test was also conducted on a fracture with various water heads to investigate the sensitivity of transmissivity to the flow rate (Reynolds number). The test results showed non-Darcy pressure drop behaviour, which changes at different shear displacements with different geometries of void spaces. The related numerical simulations by solving Navier-Stokes equations have proven this phenomenon, and have helped find that the presence of vertex at high Reynolds numbers may be the principal factor inducing the nonlinearity relation of flow rate and water pressure.
1. Design of testing apparatus

1.1 Direct shear testing apparatus

1.1.1 Hardware of apparatus

A novel servo-controlled direct shear apparatus, shown in Photo 1.1, is designed and fabricated for the purpose of testing both natural and artificial rock fractures under various boundary conditions (Jiang et al. 2001). The outline of the fundamental hardware configuration of this apparatus is described in Fig. 1.1, which consists of the following three units:

1) A hydraulic-servo actuator unit.
This device consists essentially of two load jacks that apply almost uniform normal stress on the shear plane. Both normal and shear forces are applied by hydraulic cylinders through a servo-controlled hydraulic pump. The loading capacity is 400 kN in both the normal and shear directions. The shear forces are supported through the reaction forces by two horizontal holding arms. The applied normal stress can range from 0 to 20MPa, which simulates field conditions from the ground surface to depths of about 800m.

2) An instrument package unit.
In this system, three digital load cells (tension-contraction type, capacity 200 kN (normal), 400 kN (shear)) for measuring shear and normal loads are equipped with rods connecting to the two sides of the shear box (Fig. 1.1 (a)). Displacements are monitored and measured through LVDTs (Linear Variation Displacement Transducers), which are attached on the top of the upper shear box.

3) A mounting shear box unit.
As shown in Fig. 1.2, the shear box consists of lower and upper parts, the upper box is fixed and the fracture is sheared by moving the lower box. The upper box is connected to a pair of rods to allow vertical movement and prevent lateral movement. The shear box is capable of shear tests on specimen with maximum length of 500mm and maximum width of 100mm.
1.1.2 Digitally controlled data acquisition and storage system

In the novel apparatus, the constant and variable normal stiffness control conditions are reproduced by digital closed loop control with electrical and hydraulic servos. It uses nonlinear feedback and the measurement is carried out on a PC through a multifunction analog-to-digital, digital-to-analog and digital input/output (A/D, D/A and DIO) board, using the graphical programming language LabVIEW, with a custom built ‘virtual instrument’ (VI) and a PID control toolkit.

Fig. 1.3 shows that the novel digital direct shear apparatus (Fig. 1.3(b), (c)) differs from the conventional direct shear apparatuses that equipped a set of springs (Fig. 1.3 (a)), the normal load is adjusted based on the feedback hydraulic-servo controlled value. The normal loads are monitored by compression load cells and change with the vertical displacement of fractures during the shear process represented by the sign of the feedback, which is calculated based on the normal stiffness value, $k_n$, as follows:
Fig. 1.1 Sketch view of the digital-controlled shear testing apparatus. (a) side view, (b) front view.
Fig. 1.2 Structure of shear box and preparation of artificial fracture sample.

\[
\Delta P_n = k_n \cdot \Delta \delta_n \quad (1.1)
\]

\[
P_n(t + \Delta t) = P_n(t) + \Delta P_n \quad (1.2)
\]

where \( \Delta P_n \) and \( \Delta \delta_n \) are the changes in normal load and vertical displacement, respectively. Data acquisition and normal stiffness setting are carried out digitally using 16-bit A/D and D/A boards installed in a computer.

Fig. 1.4 is a LabVIEW monitoring interface showing the front panel of the ‘shear screen’ VI. Users can set the boundary conditions (normal stress, normal stiffness, etc.) and operate the shear process (start, pause, shear rate, etc.) on this screen. Status information and the collected data curves can be presented on indicators in real time during shear tests.
Fig. 1.3 Principle of reproducing the CNS condition during the shear process in the novel direct shear apparatus. (a) CNS test on conventional apparatus, (b) CNS test on the novel apparatus, (c) method for the representation of CNS condition.

1.2 Coupled shear-flow-tracer testing apparatus

1.2.1 Fundamental hardware configuration

Fluid flows through a rough fracture following connected channels bypassing the contact areas with tortuosity. These phenomena cannot be directly observed in ordinary laboratory tests without a visualization device. In this study, based on the direct shear testing apparatus, a laboratory visualization system of shear-flow tests under the CNS
**Fig. 1.4** A LabVIEW screen showing the front panel of the ‘shear main screen’ VI. The user controls and sets the CNS operation on this screen. Status information and the collected data curves are presented on indicators.

boundary condition is developed. The outline of the fundamental hardware configuration of this apparatus is depicted in Fig. 1.5. Besides 1) hydraulic-servo actuator unit, 2) instrument package unit and 3) mounting shear plate unit as depicted in section 1.1, 2 other units are further equipped as follows.

4) A water supplying, sealing and measurement unit. Constant water pressure is obtained from an air compressor connecting to a water vessel. The water pressure is controlled with a regulator ranging from 0 to 1 MPa. The two sides of specimen parallel to the shear direction are sealed with gel sheets, which are very flexible with perfect sealing effect and minimum effect to the mechanical behaviour of the shear testing. The weight of water flowing out of the fracture is measured by an electrical balance in real time.
Fig. 1.5 Schematic view of the coupled shear-flow test apparatus. (a) Normal and shear load units, (b) hydraulic test mechanism.
5) A visualization unit. When acrylic transparent replicas of rock fractures with natural surface features are used as the upper block of a fracture specimen in tests, the images of the fluid flow in the fractures are captured by a CCD camera through an observation window on the upper shear plate. Dye can be used to enhance the visibility of the flow paths.

1.2.2 Application of visualization technique

A close view of the visualization unit is shown in Fig. 1.6. One significant change has been made on the loading unit to facilitate the visualization function. As can be seen in the figure, the normal loading is applied upwards from the bottom of lower shear box and one observation hole was opened on the plate of upper shear box so that the CCD camera placed above can directly capture the flow images in the rock fracture. In tracer test, utilizations of transparent acrylic specimen and dye provide high-quality flow images that can be used in image processing to digitize the flow characteristics.

In a flow image, the chroma of the dye color changes with the thickness of dyed water point by point. In order to find out the relationship between the chroma of flow images and the aperture (thickness of dyed water and also of void spaces), a few prior flow tests were conducted on two parallel plate specimens with inclined opening widths as demonstrated in Fig. 1.7. In these tests, the aperture between the upper acrylic specimen and the lower plaster specimen increases linearly from 0 to some specific values (e.g. 1mm, 2mm). Then, normal water and dyed water were injected into the fracture respectively until filling all the void spaces. The flow images of normal water and dyed water were captured by CCD camera and analyzed by image processing software. Herein, each image is divided into 1024×1024 elements and the chroma value of each element was calculated. The difference of the chroma values obtained from normal water flow and dye flow is the increment of chroma at each element induced by the dye. Therefore, by taking the difference of normal water flow image and dye flow image, the background of fracture surface and the reflection on the surface of acrylic specimen can be eliminated, remaining only the chroma increment introduced by dye at each element. One test result of the relationship of chroma and aperture evaluated from flow images is shown in Fig. 1.8, which can be represented by a mathematical equation as follows:

\[ e_c = 0.0318C^{1.2062} \]  

(1.3)
Fig. 1.6 Modified shear box for coupled shear-flow-tracer test. (a) Schematic view of the visualization process during coupled shear-flow tests, (b) sample set of transparent acrylic and plaster replicas for upper and lower parts, respectively.

where \( e_v \) is the aperture evaluated by flow images, \( C \) is chroma of dye.

By changing the maximum aperture (open width at right side in Fig.1.7) in the tests, coincident curves have been obtained and the validity of the parameters in Eq. (1.3) has been clarified. Using this equation, the mechanical aperture can be evaluated at each element by image processing during shear-flow processes.
Fig. 1.7 Demonstration of the cuneal aperture used for assessing the relation of mechanical aperture and chroma value.

Fig. 1.8 Relation between the aperture $e_v$ in a fracture and chroma value $C$. 
2. Fracture sample preparation and test procedure

2.1 Sample preparation

A series of fracture samples with different surface characteristics were used in direct shear, coupled shear-flow and coupled shear-flow-tracer tests.

Four rock fracture specimens, labeled as J1, J2, J3 and J4 (Figs. 2.1 (a), (b), (c) and (d)), were taken from the construction site of Omaru power plant in Miyazaki prefecture in Japan (Jiang et al., 2005, Li et al., 2006), and were used as prototypes to produce artificial replicas of rock fractures which were used in the direct shear (J4) and coupled shear-flow tests (J1-J3). Among these fracture specimens, J1 and J4 are flat with very few major asperities on its surface. The surface of J2 is smooth but a major asperity exists at the center, and a few other large asperities on other locations. J3 is very rough with no major asperities but plenty of small ones. The specimens (replicas) are 100mm in width, 200mm in length and 100mm in height, and were made of mixtures of plaster, water and retardant with weight ratios of 1: 0.2: 0.005. The mechanical properties of these rock-like specimens are shown in Table 2.1. The surfaces of the natural rock fractures were firstly re-cast by using the resin material to create a firm basic module, then the two halves of a specimen were manufactured based on the resin replica. The geometrical models constituted from the scanning data of the rock replicas re-cast from the same resin model are well matched even to the small asperities in a scale of 0.2mm. Therefore, the two halves of these specimens are almost perfectly mated.

<table>
<thead>
<tr>
<th>Table 2.1 Physico-mechanical properties of specimen.</th>
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<tbody>
<tr>
<td>Physico-mechanical properties</td>
</tr>
<tr>
<td>Density</td>
</tr>
<tr>
<td>Compressive strength</td>
</tr>
<tr>
<td>Modulus of elasticity</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
</tr>
<tr>
<td>Tensile strength</td>
</tr>
<tr>
<td>Cohesion</td>
</tr>
<tr>
<td>Internal friction angle</td>
</tr>
</tbody>
</table>
Fig. 2.1 3-D models of surface topographies of specimens J1-J4, J6 and J7 based on the measured topographical data. It should be noted that the size of mesh used in this figure is 2mm different from the one used in measurement 0.2mm.
Brazilian test was applied on sandstone and granite blocks to generate fresh artificial fractures as shown in Fig. 2.2. During the test, normal load was firstly applied to some appropriate values like 10KN (inducing no destruction to the block), and then lateral loads were applied through the wedges. The magnitude of the lateral loads needs several attempts for different kinds of rocks to ensure successful generation of fracture. Keeping the lateral loads unchanged, the normal load then was gradually decreased until the generation of tensile fracture was accomplished. Two fractures were generated as shown in Figs. 2.1 (e) and (f). J6 and J7 don’t have obvious major asperities on the surfaces and their roughness are a little larger than J1 but smaller than J2. The two opposing surfaces of the tensile rock fracture were firstly re-cast by using silicon rubber separately and then the upper and lower parts of a fracture specimen were manufactured based on the silicon rubber, respectively. The transparent upper part of the fracture specimen was made of acrylic and the lower part was plaster sample. The process to manufacture the transparent sample is demonstrated in Fig. 2.3. The air bubbles in the liquid acrylic material were carefully eliminated during the manufacture, so that the production of sample is of high transparency. The curing time of the transparent specimen was carefully chosen to ensure its uniaxial compressive strength is close to the lower plaster specimen. By doing so, the artificial fracture using acrylic-plaster pair exhibits reasonably close mechanical behaviour with the normal plaster-plaster pair. The two halves of fracture specimen used in this study are not always perfectly mated as the initial condition due to the sample damage observed during creating tensile fractures by Brazilian test and unavoidable relocation errors before testing.
(1) Setting tensile rock sample as prototype

(2) Manufacturing silicon sample. Deaeration by slight shaking.

(3) Setting silicon sample

(4) Preparing liquid acrylic material. Deaeration by putting the vessel in an airproof container and applying vacuum pressure.

(5) Injecting liquid acrylite into the mold to cast the surface of silicon sample.

(6) Covering an acrylic cube on the liquid acrylite to accomplish a transparent sample.

**Fig. 2.3** Manufacturing process of transparent sample prepared for the coupled shear-flow-tracer tests.
2.2 Test procedures

The boundary conditions (normal stress/normal stiffness) applied in the direct shear tests, coupled shear-flow and coupled shear-flow tracer tests are summarized in Table 2.2. Among them, J4 was employed in direct shear test, J1-3 were employed in coupled shear flow test, J6-7 were employed in coupled shear-flow test. In the direct shear tests, the shear rate was set to 0.5mm/min, and the shear stress, shear displacement, normal stress and normal displacement were recorded. In the coupled shear-flow and coupled shear-flow tracer tests, the flow direction is parallel to the shear direction and the cubic law was used to evaluate the transmissivities based on the measured flow rates. The water head was applied at an interval of 1mm during the shear process. When the water pressure was applied, the shear was temporarily stopped until the measurement of water volume flowing out of fracture was finished. For cases J1-J3 and J6, a water head of 0.1m was applied as a basic pattern during the tests. When a shear goes on, dilation of fracture takes place, remarkably increasing the flow rate as well as Reynolds numbers. To avoid the appearance of turbulent flow, the water head applied to fracture needs to decrease gradually in a shear process. Therefore, 3 patterns of water head were applied at each measurement, with water head 0.1m unchanged and the other two patterns decreasing gradually along with shear displacement. For case 7, at each 1mm of shear displacement, more than 5 different water heads were applied to investigate the sensitivity of transmissivity to the water head. The measurement of water volume was conducted by electrical balance and the weight of water was measured at an interval of 1 second up to 50 seconds to get the mean value in the steady stage of flow. The total shear displacements for J1, J2 and J3 is 18mm, for J4 is 20mm and for J6 and J7 is 15mm, all of which are enough to shear the rock fractures to the residual stage.

As a shear goes on, the effective shear length (the length of the upper and lower halves of specimen facing to each other) will decrease, thus increasing the hydraulic gradient when the water head keeps constant. This effect has been considered in calculation of the transmissivity by decreasing the hydraulic gradient corresponding to the shear displacement.

2.3 Measurement of surface roughness

To obtain the topographical data of rock fracture surfaces, a three-dimensional laser scanning profilometer system (Fig. 2.4), which has an accuracy of ±20μm and a resolution of 10μm, was employed. A X-Y positioning table can move automatically
Table 2.2 Experiment cases under CNL and CNS boundary conditions.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Case No.</th>
<th>Roughness (JRC range)</th>
<th>Boundary condition</th>
<th>Initial normal stresses $\delta_n$ (MPa)</th>
<th>Normal stiffness $k_n$ (GPa/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>J1</td>
<td>J1-1</td>
<td>0~2</td>
<td></td>
<td>1.0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>J1-2</td>
<td></td>
<td></td>
<td>1.5</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>J1-3</td>
<td></td>
<td></td>
<td>1.0</td>
<td>0.5</td>
</tr>
<tr>
<td></td>
<td>J2-1</td>
<td></td>
<td></td>
<td>1.0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>J2-2</td>
<td>12~14</td>
<td></td>
<td>2.0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>J2-3</td>
<td></td>
<td></td>
<td>1.0</td>
<td>0.5</td>
</tr>
<tr>
<td></td>
<td>J3-1</td>
<td></td>
<td></td>
<td>1.0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>J3-2</td>
<td>16~18</td>
<td></td>
<td>1.0</td>
<td>0.2</td>
</tr>
<tr>
<td></td>
<td>J3-3</td>
<td></td>
<td></td>
<td>1.0</td>
<td>0.5</td>
</tr>
<tr>
<td></td>
<td>J4-1~J4-3</td>
<td></td>
<td></td>
<td>1.0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>J4-4~J4-6</td>
<td>0~2</td>
<td></td>
<td>2.0</td>
<td>3.0</td>
</tr>
<tr>
<td></td>
<td>J4-7~J4-9</td>
<td></td>
<td></td>
<td>5.0</td>
<td>7.0</td>
</tr>
<tr>
<td>J6</td>
<td>J6-1</td>
<td>2~4</td>
<td></td>
<td>1.0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>J6-2</td>
<td></td>
<td></td>
<td>1.5</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>J6-3</td>
<td></td>
<td></td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>J7</td>
<td>J7-1</td>
<td>6~8</td>
<td></td>
<td>1.0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>J7-2</td>
<td></td>
<td></td>
<td>1.5</td>
<td>0</td>
</tr>
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</table>

Fig. 2.4 Schematic view of the 3-D laser scanning instrument for measuring fracture surface.
under the sample by pre-programmed paths to measure the desired portion of the sample surface. A PC performs data collecting and processing in real time.

The specimens were measured in both shear direction and the direction perpendicular to the shear direction with the same sampling interval of 0.2mm for obtaining sufficient data for 3-D fractal evaluation and numerical model construction.

3. Influence of surface roughness on shear behaviours of rock fracture

3.1 Fractal dimension evaluation method

Fractal dimension measured on a sectional profile ranges $1 \leq D \leq 2$. Because of the anisotropy and heterogeneity of fracture surface topography, fractal measurement based on sectional profiles is questionable. In this thesis, a direct 3-D fractal evaluation method, the projective covering method (PCM) proposed by Xie et al. (1993), is used to directly estimate the real fractal dimension in the range of $2 \leq Ds \leq 3$ for a fracture surface.

In this method, a corresponding projective network $B$ is set to cover a real fracture surface $A$ as shown in Fig. 3.1. This fracture surface is then divided into a large number of small squares by a selected scale of $\delta$ (Fig. 3.1(a)). In the $k$th square $abcd$ (Fig. 3.1(b)), the heights of the fracture surface at four corner points $a$, $b$, $c$ and $d$ have the values of $h_{ak}$, $h_{bk}$, $h_{ck}$ and $h_{dk}$. The area of rough surface surrounded by points $a$, $b$, $c$ and $d$ can be approximately calculated by

$$A_k(\delta) = \frac{1}{2} \left\{ (\delta^2 + (h_{ak} - h_{ck}))^{\frac{E}{2}}, (\delta^2 + (h_{ak} - h_{ck}))^{\frac{E}{2}} \right\}$$

$$+ \left\{ (\delta^2 + (h_{ak} - h_{dk}))^{\frac{E}{2}}, (\delta^2 + (h_{ak} - h_{ck}))^{\frac{E}{2}} \right\}$$

The entire area of the rough surface under $k$th scale measurement is given by

$$A_T(\delta) = \sum_{k=1}^{N(\delta)} A_k(\delta)$$

In fractal geometry, the measure of a fractal object in an $E$-dimensional Euclidean space can be expressed in a general form (Xie, 1993):

$$G(\delta) = G_0 \delta^{E-D_s}$$

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Fig. 3.1 The projective covering method (PCM). (a) A fracture surface A and its corresponding projective network B, (b) the $k$th projective covering cell.

where, $E$ represents the Euclidean dimension. If $E=2$, $G$ and $\delta$ in Eq. (3.3) correspond to a fractal area, then Eq. (3.3) yields

$$A_f(\delta) = A_{r0}\delta^{2-D_s}$$  \hspace{1cm} (3.4)
where $A_{r0}$ denotes the apparent area of the rough surface. From Eqns. (3.2) and (3.4), we have the following relation:

$$A_r(\delta) = \sum_{k=1}^{N(\delta)} A_k(\delta) \sim \delta^{2-D_s}$$

where $D_s$ is the real fractal dimension of a rough surface.

The surface of J4 was measured before and after shearing for the tests under different boundary conditions, and $D_s$ values were calculated based on this method. Their relations will be discussed in the next section.

3.2 Correlations of mechanical properties with fractal dimension of rock fractures

3.2.1 Shear strength

Fig. 3.2 shows the test result of J4 when initial normal stress is 1MPa and normal stiffness are 0, 3, 7GPa/m, respectively. For all tests, the shear stresses are greater under CNS condition because of the increased normal stress caused by dilation during shearing. Comparing the test results with other samples, it can be found that the shear stress increases with a larger initial normal stress and a higher value of JRC. Moreover, it is shown in Fig. 3.2 (b) that the normal displacement controls the mechanical aperture of fracture, and changes significantly when a normal stiffness is applied to the sample, due to the increase of normal stress with shear displacement. The change of normal displacement in CNS tests is small in comparison with that in CNL tests.

3.2.2 3-D fractal dimension with correlation to fracture properties

In nature, rock blocks shearing along fracture surfaces is a generally 3-D phenomenon. 2-D fractal dimension, however, only describes a part of surface characteristics, with a few sectional profiles. Consequently, using the 2-D fractal dimension to build the prediction equation on shear strength, may neglect a large part of geometrical information of natural rock fracture surfaces and, therefore, may not give reliable estimation. In view of the fact that there are few literatures presenting shear behaviour investigations by application of 3-D fractal dimension, this study attempts to propose a new approach in this area.
Fig. 3.2 Shear and dilation behaviors of rock fractures. (a) Shear stress versus shear displacement, (b) Normal displacement versus shear displacement. (J4-1, $\sigma_{n0}=1$MPa)

Shear tests with the initial normal stresses of 1MPa, 2MPa and 5MPa under CNL, CNS ($k_n=3$GPa, $k_n=7$GPa) conditions, 9 cases in total, were carried out on specimen J4. Generally, surfaces of specimens turn to become smoother after shearing, and this change can be quantified by changes in the 3-D fractal dimension $D_s$. As shown in Fig. 3.3, $D_s$ declines with larger initial normal stress and normal stiffness. These plots present a stronger relation between boundary conditions and $D_s$ in shearing than that exhibited by the 2-D fractal dimension presented in former studies, therefore $D_s$ could be a better parameter to be used in correlation to the shear behaviour of natural rock fractures.

5 sectional profiles were measured on J4 and a mean JRC value of 1.5 was obtained by using the equation developed by Tse and Cruden (1979). It is of interest to compare the shear results with the commonly used empirical equation proposed by Barton and Choubey (1977). In this equation, values of four variables need to be investigated to predict shear strength. Herein, $\sigma_n$ has certain values at initial conditions and the measured JCS by using Schmidt rebound hammer is 39MPa. $\phi_0$ can be obtained directly from shear tests. By using Barton’ empirical equation, the predicted shear strength values were calculated and compared with the experiment data as shown in Fig. 3.4. Predicted values show reasonably good consistency with the measurements, improving the capability of Barton’s equation to the prediction of natural rock fractures. It should be noticed that the surface of specimen J4 is very smooth and the inclination of fracture was also negligible. In the former studies, Barton’s equation has overestimated shear strength at a relatively high normal stress and therefore caution is still needed for applications with rock fractures of more complex surface geometries.
Fig. 3.3 Relationship between fractal dimension $D_s$ and initial normal stress under boundary conditions of CNL, CNS ($k_n=3\text{GPa/m}$) and CNS ($k_n=7\text{GPa/m}$).

Fig. 3.4 Comparison of shear strength of specimen J4 from experiment tests (under CNL condition) and predicted with Barton’s empirical equation.
4. Coupled shear-flow-tracer test on single rock fractures

4.1 Evaluation of aperture evolution during coupled shear-flow tests

The changes of aperture distributions corresponding to the coupled shear-flow tests were simulated based on the measured topographical data. Mechanical apertures can be assessed using the following equation (Esaki et al. 1999):

\[ E_m = E_0 - \Delta E_n + \Delta E_s \]  

where \( E_0 \) is the initial mechanical aperture, \( \Delta E_n \) is the change of mechanical aperture by normal loading, and \( \Delta E_s \) is the change of mechanical aperture induced by shearing. By using the normal stress-normal displacement curves, the initial mechanical aperture \( E_0 \) under a certain normal stress can be obtained. Under the CNL boundary condition, \( \Delta E_n \) could be taken as a constant, and \( \Delta E_s \) is the measured normal displacement during shearing. For the test under the CNS boundary condition, the normal stress changes with the normal displacement, therefore, \( \Delta E_n \) itself should be revised due to the corresponding normal stress during shearing and \( \Delta E_s \) is also the measured normal displacement.

In the present study, the surfaces of fracture specimen were scanned with an interval of 0.2mm in \( x \) and \( y \)-axes, and the mechanical aperture under the CNL boundary condition at any point \((i, j)\), where \( i \) is parallel to the shear direction and \( j \) is perpendicular to the shear direction at shear displacement \( u \) could be written as:

\[
E_m(i, j) = E_0(i, j) + E_s(i, j) \\
= E_0(i, j) + [V(u) + Z_U(i + u, j) - Z_L(i, j)] \\
= Z_U(i + u, j) - Z_L(i, j)
\]  

where \( V(u) \) is the normal displacement (dilation) at a shear displacement of \( u \) intervals, \( i+u \) indicates the point number of the upper surface that directly mates with the current point \( i \) at the lower surface. \( Z_U \) and \( Z_L \) represent the heights of the upper and lower surfaces of the fracture specimen at any points from the lowest point of the lower surface, respectively.

Eq. (4.2) is valid when the following conditions could be satisfied: (1) normal displacement totally contributes to the dilation of the mechanical aperture, (2) the
deformation or damage of asperities could be neglected, (3) gouge materials developed during shearing have negligible influence on the fluid flow. Obviously, these conditions cannot be generally satisfied and the method used here therefore is a simplified one.

4.2 Coupled shear-flow test results

As shown in Fig. 4.1, the changes of transmissivities exhibit an obvious two-stage behaviour. For all test cases, the transmissivities increase gradually in a relatively high gradient in the first several millimeters of shear displacement and then continue to increase but with a lower gradient gradually reaching to zero. Similar behaviours have also been reported by Esaki (1999) and Olsson and Barton (2001) etc. The experimental results indicate that a rougher fracture may have higher gradient in the first stage and the second stage comes sooner. Under the same stress environment, a rougher fracture would produce larger normal displacement during shear so that it could obtain higher transmissivities in the second stage. The peak shear stress generally comes earlier than the turning point of transmissivity, which could be explained by the damage process of asperities on the fracture walls during shear.

Fig. 4.2 shows the changes of aperture distributions of testing cases J1-1, J2-1 and J3-1 during shearing, respectively. The aperture fields change remarkably when a shear starts, i.e. in stage 1. After that, the change trends to become smaller and steady, due to the graduate reduction of dilation gradient in stage 2. The contact ratio changes reversely to the transmissivity change in a shearing, which represents an opposite effect of contact area on the transmissivity. There is a rapid drop of contact ratio in stage 1 and then it keeps a small value in stage 2. For a rougher fracture, such reduction of contact ratio will be more significant. The peak shear stress occurs when the major asperities on the fracture surface lose their resistance to the shear and being destructed, while most asperities are undamaged and few gouge materials are generated. After that, the remaining asperities are crushed gradually, generating plenty of gouge materials and slightly increasing the contact ratio. Therefore, the turning point of contact ratio occurs at almost the same time with that of the transmissivity and the effect of contact areas on the transmissivity of rock fracture is confirmed. Since the normal loads applied in the tests are relatively low, surface damages are limited in this study.

The influences of morphological behaviours of rock fractures on the evolution of aperture distributions are also reflected in Fig.4.2. The surface of specimen J1 is smooth and flat. Therefore, its contact ratio is relatively high and its apertures distribute evenly over the fracture specimen. The few large asperities on the two parts of specimen J2
Fig. 4.1 Two-stage behavior of the change of conductivity during shearing. A minus dilation of fracture occurs when a shear starts which causes the decrease of conductivity in stage 1. After this, a rapid increase happens till the second phase in which the conductivity trends to keep constant.
Fig. 4.2 Comparison of the change of mechanical aperture $h_M$, hydraulic aperture $h_H$ and contact ratio $c$ of specimens J1-1, J2-1 and J3-1 during shearing. The upper three figures in figures (a), (b) and (c) show the distributions of mechanical apertures at shear offsets of 2mm, 8mm and 16mm, respectively. The white parts in these figures are the contact areas. The contact ratios at the initial state (0 shear displacement) for each case were assumed to be 0.9 since the fracture specimens were almost perfectly mated.

...tended to climb over each other during shear, which decreased the contact ratio significantly and produced a large void space after a section of shear displacement (see the third figure in Fig.4.2 (b)). For specimen J3, the widely distributed asperities developed a complicated void space geometry, which caused complex structure of transmissivity field (Fig.4.2 (c)).
4.3 Coupled shear-flow-tracer test results

Application of a high resolution CCD camera and its related image processing software was conducted in the coupled shear-flow-tracer tests on J6 and J7 and the flow images were digitized to obtain the numerical data of the flow features like aperture distributions and flow rates.

Comparisons of the flow images (photos), the aperture $e_v$ distributions and mechanical aperture distributions of the case J6-1 are shown in Fig. 4.3. The pictures clearly show the contact area distributions and their changes during shear. The contact areas were gradually localized while decreasing its ratio during shear and the dye flows bypassing the contact areas. The relations of mechanical aperture $E$, hydraulic aperture $h$ and aperture evaluated from flow images $e_v$ obtained from test results of J6 are shown in Fig. 4.4. As demonstrated in Fig. 4.4, generally, $e_v$ has close values with $h$ in all cases. The evolution of apertures in a shear process generally exhibits a two-stage behaviour as aforementioned. In the first stage of shear when contact areas dominate the fracture surface, the mechanical apertures are small and water flows through a fracture from many connected small channels as shown in Fig. 4.3 (3mm). As shear advances, the dilation of fracture trigger the emergence of more void spaces in a fracture, providing abundant channels for water to pass through. At the same time, a few major channels begin to emerge (5mm). After entering stage 2 in a shear process, the fluid flows through a fracture bypassing a few major contact areas, concentrating in a few major channels (8-15mm). Fig. 4.3 (c) employed Eq. (1.3) to assess the mechanical aperture distributions during shearing, in which the aperture distribution patterns are similar to flow images (a). The dark portion at the right part in figures (c) at 8 and 15mm of displacements indicate the existence of a large void space. In flow images (a), however, contacts appear in the same portion, which was confirmed as water bubbles by opening the aperture after test. The existence of water bubbles in the fracture could be considered as the main reason that caused the deviations of mechanical aperture and hydraulic aperture especially in stage 2. If the water could fill all the void spaces in a fracture, the aperture $e_v$ may provide closer value to the mechanical aperture since it essentially measures the mean width of void spaces occupied by water flow in a fracture. Close values of $e_v$ and $h$ reveal that in the void spaces where water flow exist, mechanical aperture agrees well with hydraulic aperture.

J7-1 is a specially designed case by applying various water heads at each shear displacement to investigate the sensitivity of transmissivity to water pressure. The
relations of flow rates and water heads at shear displacements from 3mm to 13mm are shown in Fig. 4.5. The full shear-flow process of this case also follows the 2-stage behaviour as depicted in case J1–J3. In shear displacements of 3mm-4mm, the flow rates increase proportionally with the water heads, with the hydraulic gradient as high as 4.2, indicating the validity of Darcy’s law in this stage. After the generation of major flow channels, the nonlinearity of the relation between flow rates and water heads begin

Fig. 4.3 Flow field and aperture evolution during shear process of case 2. (a) Flow images, (b) aperture obtained by image processing on flow images, (c) mechanical aperture distribution by means of topographical data of fracture surface.
Fig. 4.4 Relations of mechanical aperture $E$, hydraulic aperture $h$ and aperture evaluated from flow images $e_v$.

to emerge when water heads exceed some values, which change at different shear displacements with the evolution of void geometries. At each shear displacement, taking the transmissivity when the relation between flow rates and water pressures keeps linear (i.e. at extremely low water heads) as $T_0$, the normalized transmissivity $T/T_0$ of all measurements through the whole shear process against Reynolds number is shown in Fig. 4.6. The normalized transmissivity starts to drop when Reynolds number becomes larger than around 10, and the value of transmissivity decreases to 80% by the Reynolds number of around 50, which agrees with the results presented by Zimmerman et al. (2004). Then, the decreasing gradient becomes small and the transmissivity drops 10%-20% when Reynolds number increases from 50 to 200. The decrease of transmissivity at high Reynolds numbers may originates from the nonlinear Forchheimer effect, which will be further discussed in the numerical simulations.

5. Numerical simulations of coupled shear-flow-tracer tests
Fig. 4.5 Relations of flow rate of water head for shear displacement 3mm~13mm.

Fig. 4.6 Relations of normalized transmissivity with Reynolds number for shear displacement 3mm~13mm.

5.1 Numerical simulation methodology

For a single fracture, fluid flow is governed by the Navier-Stokes equations, which can be written as (Batchelor, 1967)
\[
\frac{\partial u}{\partial t} + (u \cdot \nabla)u = F - \frac{1}{\rho} \nabla p + \frac{\mu}{\rho} \nabla^2 u
\]  

(5.1)

where \( u = (u_x, u_y, u_z) \) is the velocity vector, \( F \) is the body-force vector per unit mass, \( \rho \) is the fluid density, \( \mu \) is the fluid viscosity, and \( p \) is the pressure. In the steady state, the Navier-Stokes equations then reduce to

\[
\mu \nabla^2 u - \rho (u \cdot \nabla) u = \nabla p
\]

(5.2)

An additional continuity equation, which is deduced from the law of conservation, is introduced to close the system.

\[
\text{div} u = \nabla \cdot u = \frac{\partial u_x}{\partial x} + \frac{\partial u_y}{\partial y} + \frac{\partial u_z}{\partial z}
\]

(5.3)

The advective acceleration term \((u \cdot \nabla)u\) is the source of nonlinearity in the NS equations, which makes the equations difficult to solve. In engineering practices, simplified forms of NS equation are commonly used. 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:

\[
\frac{\partial}{\partial x} \left( T_{xx} \frac{\partial h}{\partial x} \right) + \frac{\partial}{\partial y} \left( T_{yy} \frac{\partial h}{\partial y} \right) + Q = 0
\]

(5.4)

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:

\[
T_{xx} = T_{yy} = T(x,y) = \frac{Dgb^3}{12\mu}
\]

(5.5)
where $b$ is the aperture of a fracture. Applying Galerkin method to the Eq. (5.4), the discretized governing equation becomes as follows:

$$
\sum_{m=1}^{N} \left[ K^{(m)} \right] \hat{h}^{(m)} = \sum_{m=1}^{N} \left[ F^{(m)} \right] \quad (5.6)
$$

with

$$
[K^{(m)}] = \int_{S^{(m)}} \left[ B^{(m)} \right]^T \left[ D^{(m)} \right] B^{(m)} dS
$$

$$
[F^{(m)}] = \int_{e^{(m)}} \left[ N^{(m)} \right]^T Q^{(m)} dS - \int_{e^{(m)}} \left[ N^{(m)} \right]^T \left( T \frac{\partial h}{\partial x} n_x + T \frac{\partial h}{\partial y} n_y \right) dL \quad (5.7)
$$

where $N$ is the number of element, $[K^{(m)}]$ is transmissivity matrix, $\{h^{(m)}\}$ is hydraulic head vector, $\{F^{(m)}\}$ is flux vector, $[N^{(m)}]$ is the shape function in the element $m$, $S^{(m)}$ is the surface of the element, $L^{(m)}$ is the boundary in which the flow rate is known, $n_x$ and $n_y$ are the unit normal vector to the boundary in $x$ and $y$ direction. The matrix $[D^{(m)}]$ and $[B^{(m)}]$ is defined as follows respectively:

$$
[D^{(m)}] = \begin{bmatrix}
T & 0 \\
0 & T
\end{bmatrix}
= \begin{bmatrix}
\frac{\rho_f gb^{(m)^3}}{12 \mu} & 0 \\
0 & \frac{\rho_f gb^{(m)^3}}{12 \mu}
\end{bmatrix} \quad (5.8)
$$

$$
\begin{bmatrix}
i_x \\
i_y
\end{bmatrix} = \begin{bmatrix}
\frac{\partial h}{\partial x} \\
\frac{\partial h}{\partial y}
\end{bmatrix} = \begin{bmatrix}
\partial \left[ N^{(m)} \right]^T \\
\partial \left[ N^{(m)} \right]^T
\end{bmatrix} \begin{bmatrix}
i^{(m)} \\
\hat{h}^{(m)}
\end{bmatrix} = [B^{(m)}] \hat{h}^{(m)} \quad (5.9)
$$
The transmissivity of each element was calculated from Eq. (5.5) using the mean aperture of each element. To solve Eq. (5.6), the commercial software, COMSOL Multiphysics was used in this study. The digitized aperture map of the fracture specimen was divided into 20000 (200 × 100) small square elements of an edge length of 1.0 mm.

Mechanical aperture of each mesh (1mm × 1mm) during shear can be assessed by using Eq. (4.13). Numerical shearing can be simulated by moving the upper surface by a horizontal translation of 1 mm in the shear direction, then uplifting the upper surface by the dilation increment according to the measured mean shear dilation value at that shear interval as shown in Fig. 5.1.

Both unidirectional flows parallel with and perpendicular to the shear direction were considered in the flow simulations by fixing the initial hydraulic heads of 0.1 m and 0 m along the left- and right-hand boundaries for the flow parallel with the shear direction (Fig. 5.2a), and the bottom and top boundaries for the flow perpendicular to the shear direction (Fig. 5.2b), respectively.

In this study, contact areas/elements were numerically eliminated from the calculation domain and their boundaries were treated as additional internal boundaries with a zero flux condition \( \frac{\partial h}{\partial n} = (\nabla h) \cdot n \), where \( n \) is the outward unit normal vectors.

![Diagram of mechanical aperture](image)

**Fig. 5.1** Estimation of the mechanical aperture in a shear process by using digitized geometrical models of the upper and lower surface of a fracture.
Fig. 5.2 Boundary conditions for the flow model, (a) parallel with and (b) perpendicular to the shear displacement, and (c) FEM mesh.

Fig. 5.3 3-D FEM model of void space for solving Navier-Stokes equations (shear displacement of 4mm, J3-1).
of the contact areas, in order to satisfy conditions of no flow into or out of the contact areas (Zimmerman et al., 1992), as shown in Figs. 5.2 (a) and (b).

With the development of computational techniques, some programs that can directly solve 3-D NS equations become available. In this study, the commercial software, ANSYS was used to simulate the coupled shear-flow test J3-1 and coupled shear-flow-tracer test J7-1 by solving 3-D NS equations in order to investigate the influence of the nonlinear term on the flow behaviours in a coupled shear-flow system. The boundary conditions are identical with that used in solving Reynolds equations as shown in Fig. 5.2. 1mm×1mm mesh was used in the 3-D model as shown in Fig. 5.3 at shear displacement of 4mm (J3-1).

5.2 Simulation results by solving Reynolds equation

5.2.1 Numerical simulation of coupled shear-flow tests

The results of flow velocities are superimposed in Fig. 5.4 and Fig. 5.5, with arrows. The grey intensity of the background in the flow areas indicates the magnitude of local transmissivities (see the legend in the figures). Figs. 5.4 (a), (b) and (c) show the flow velocity fields with transmissivity evolutions at different shear displacement of 1, 2, 5 and 10 mm for different fractures, J1, J2 and J3 under constant normal stress of 1 MPa, respectively. For J1, at 1 mm of shear displacement, the contact areas are widely and uniformly distributed over the whole fracture sample and actually blocked the fluid flow totally without any continuous flow path. Continuous flow paths start to form at 2 mm of shear displacements, and continue to grow into main flow paths with continued decrease of contact areas and increase of transmissivity, with increasing shear displacement (see the last three figures of Fig. 5.4 (a)). Similar phenomenon can be observed also for specimen J3 (Fig. 5.4 (c)). In both cases, fluid flows bypass the contact areas with less resistance and main flow paths are limited only in a few high transmissivity areas (flow channels). As a result, flow patterns (or stream lines) become very tortuous.

Fig. 5.4 (d) shows the flow velocity fields with transmissivity evolutions at different shear displacement of 1, 2, 5 and 10 mm for J1-2. Due to the much increased contact areas and much reduced transmissivity, there exists no fluid flow going through the fracture sample (contact areas blocking the fluid flow totally) up to shear displacement of 2mm, and significant flow paths can only be detected at shear displacement of 5 mm. The flow pattern for sample J2 is very different due to the different surface character.
Figure 5.4 Flow velocity fields for the fluid flow parallel with shear direction with transmissivity evolutions at different shear displacement of 1, 2, 5 and 10 mm for fracture sample, J1 under different constant normal stress, (a) J1-1 (CNL, 1.0 MPa) and (b) J1-2 (CNL, 1.5MPa).
Figure 5.4 (continued). Flow velocity fields for the fluid flow parallel with shear direction with transmissivity evolutions at different shear displacement of 1, 2, 5 and 10 mm for fracture samples J2 and J3 under constant normal stress of 1.0 MPa, (c) J2-1 and (d) J3-1.
The flow rate at the outlet boundary (along $x=0$) for all test cases with different normal loading conditions were compared between laboratory tests and numerical simulations as shown in Fig. 5.5. The general behaviours of the flow rate variation with shear displacement under different normal stress/stiffness conditions were captured for all samples, with varying degrees of general agreements. The flow rate increase very sharply in the early stage of shear (after 1 mm or 2 mm shear displacements) and continue to increase but with a progressive reduction of gradient. The general increase of flow rate is about 5-6 order of magnitude from the initial state before shear. The measured and simulated results agree well for sample J3, but less well for sample J2 and J1.

5.2.2 Simulation for shear-induced flow anisotropy

The simulated results of flow velocity fields with transmissivity evolutions when the overall flow direction was perpendicular to the shear direction are shown in Fig. 5.6. Figs. 5.6 (a), (c) and (d) show the flow velocity fields with transmissivity evolutions at different shear displacement of 1, 2, 5, 10 and 15 mm for fracture specimens J1, J2 and J3 under constant normal stress of 1 MPa (J1-1, J2-1 and J3-1), respectively. These figures clearly show the more significant channeling flows in the direction perpendicular to the shear direction.

For smooth and flat surface of specimen J1, the continuous flow paths start to form at 2 mm of shear displacements, and continue to grow into two main flow paths with increasing shear displacement (see the last four figures of Fig. 5.6 (a). The flow pattern for specimen J2 is very different (Fig. 5.6 (c)). The presence of a few large main asperities at the upper right part of the sample dominated dilation behaviour and flow field, causing totally different flow patterns for the right and left parts of the specimen J2. Similar phenomenon can be observed also for specimen J3 (Fig. 5.6 (d)) but flow patterns are more complicated with several tortuous flow channels due to the complex structure of transmissivity and flow velocity fields.

The flow rates at the outlet for the case flow direction perpendicular to shear direction are also much larger than the case flow direction parallel to the shear direction, indicating the limitations of the conventional shear-flow tests using the boundary condition with fluid flow parallel with the shear direction. Since laboratory tests with boundary condition shear direction perpendicular to flow direction still have great difficulties to overcome, further investigations on this issue will relay on the development of numerical modellings.
Fig. 5.5 Comparison of the flow rate at the outlet between laboratory experiment and numerical simulation for different fracture samples, (a) J1, (b) J2 and (c) J3. It should be noted that zero flow rate value cannot be plotted in the log scale, which is observed at the initial shear stages.
Figure 5.6 Flow velocity fields for the fluid flow perpendicular to the shear direction with transmissivity evolutions at different shear displacement of 1, 2, 5, 10 and 15 mm for fracture sample, J1 under different constant normal stress, (a) J1-1 (CNL, 1.0 MPa) and (b) J1-2 (CNL, 1.5MPa).
Figure 5.6 (continued). Flow velocity fields for the fluid flow perpendicular to the shear direction with transmissivity evolutions at different shear displacement of 1, 2, 5, 10 and 15 mm for fracture samples, J2 and J3 under constant normal stress of 1.0 MPa, c) J2-1 and d) J3-1.
5.3 Simulation results by solving Navier-Stokes equations

Assuming cubic law and Reynolds equation are valid, the transmissivity of a fracture subjected to certain constraints is a constant. Flow rate through a fracture is proportional to hydraulic gradient. In fact, however, when Reynolds number in the fracture become high, nonlinear Forchheimer effect may arise, give nonlinear relation to flow rate and water pressure as shown in Fig. 4.7.

The flow vector distributions of J3-1 at shear displacement 8mm with water head of 0.1mm are shown in Fig. 5.7, which is similar with that shown in Fig. 5.4. When increasing the water head in 3-D numerical simulation, the velocity vector distribution changes dramatically especially while bypassing contact areas.

Figs. 5.8 (a) and (b) show enlarged vector distributions behind a contact area at x-y plane with Re number of 1 and 100, respectively, and Figs. 5.8 (c) and (d) show enlarged vector distributions behind a contact area at x-z plane with Re number of 1 and 100, respectively. Vortex can be observed in Figs. 5.8 (b) and (d) with large Re number, but not in Figs. 5.8 (a) and (c) due to the nonlinear item in NS equations. The vortexes occurred at large Re numbers occupy the void spaces in a fracture but do smaller contributions to the total flow rate than the parabolic velocity profile assumed in Reynolds equation, leading to decrease of macro flow rates. Comparisons of the numerical simulation results by solving Reynolds equation and 3-D NS equations at two different water heads respectively with test results are shown in Fig. 5.9. Note that in the test, the water head is 100mm. The results by solving NS equations at low water head agree well with the result of Reynolds equation, indicating the validity of Reynolds equation solving fluid flow through rough rock fracture at low Re number. The flow

![Figure 5.7 Velocity vector distributions at shear displacement 8mm with water head of 0.1mm of J3-1.](image)
Figure 5.8 Velocity vector distributions at the portion behind a contact area with Re numbers of 1 ((a), (c)) and 100 ((b), (d)), on $x$-$y$ plane ((a), (b)) and $x$-$z$ plane ((c), (d)).

Figure 5.9 Comparison of the total flow rate between experiment and two different numerical predictions (NS and Reynolds equation).

rates obtained by solving NS equations at water head of 100mm are 20%–50% smaller than the case with water head of 0.1mm, but fit well with the test results, revealing that if a 3-D model of void geometry of rock fracture is adequately established, the flow behaviour of fluid through the void spaces of a fracture could be well interpreted by solving 3-D NS equations. Numerical simulations on case J7-1 were also conducted by solving 3-D NS equations using the void geometry at shear displacement of 10mm with
various water heads. The comparisons of simulation results with test results are shown in Fig. 5.10, including all the test points of shear displacement from 3mm to 13mm. The simulation results exhibit similar tendency with the test results. Quantitative assessment of the Forchheimer effect on the flow behavior will be conducted in the future by computing the transmissivity at all shear displacements through numerical simulations.

6. Conclusions

In this thesis, the shear behaviour, coupled shear-flow behaviour of single rock fractures have been studied through laboratory direct shear/coupled shear-flow-tracer tests with related numerical simulations by using FEM. Some results of these studies are summarized as follows:

1) Direct shear tests
   - Peak shear stress can be observed for tests conducted under the CNL boundary condition but not for all the tests conducted under the CNS boundary condition, since the shear stress can continuously increase in the residual stage due to the increase of normal stress in some rough fractures under the CNS boundary condition.
   - The peak shear stress occurs when the major asperities on the fracture surface lose
their resistance to the shear, while most asperities with lower importance are undamaged. After that, the remaining asperities are crushed gradually if the normal constraints are large, decreasing the contact ratio and generating gouge materials.

- The shear strength is observed to increase with the increases in initial normal stress and normal stiffness. As the dilation occurs for rough fractures under CNS boundary condition, the normal stress acting on the interface increases, thus contributing to an increased value of shear stress. This increase of normal stress also leads to smaller dilation under the CNS boundary condition than the CNL boundary condition at the same initial normal stress.

- The surface of a rock fracture is a 3-D object, and the 2-D methods based on discrete and independent cross-sectional profiles could only measure a part of the roughness characteristics. 3-D fractal evaluation method, such as projective covering method, can provide a more integrated assessment to the surface roughness of rock fracture and can be better variable for shear strength prediction.

- Barton’s criterion provides good predictions of shear strength to the experimental results. However, overestimation of Barton’s criterion has been observed at some high normal stress (i.e. larger than 10MPa) with rough rock fractures, which requires further experimental verifications.

2) Coupled shear-flow-tracer tests

- It has been observed and confirmed that fluid flows through a rough fracture following connected channels bypassing the contact areas with tortuosity, not only by theoretical predictions or numerical simulations but also from direct observation of flow images through the utilization of visualization technique.

- Since the CNS boundary condition can inhibit dilation in a shear process, the transmissivity of a rock fracture under CNS boundary condition in a shear can be much smaller than that under CNL boundary condition depending on the initial normal stress, normal stiffness and surface roughness of the tested fracture.

- The ‘minus dilation’ happening at the initial shear displacement (usually less than 2mm) could significantly decrease the transmissivity of a rock fracture, preventing fluid flowing through the fracture. After that, the transmissivity increases quickly (stage 1) until a threshold, and the gradient of transmissivity trends to 0 subsequently (stage 2). Comparing to a flat fracture, a rough fracture could obtain higher value of transmissivity in stage 2 and the threshold of stage 1 would come earlier. The change of contact ratio in a shear is just opposite to that
of transmissivity.

- The numerical models using digitized fracture surfaces can be an effective approach to assess the evolution of mechanical aperture and contact area distributions in a shear process. Its validity has been verified by comparing the simulation results to the flow images obtained from the coupled shear-flow-tracer tests with visualization of the fluid flow.

- The cubic law performs reasonably well without need for any modifications for most tests on rough rock fractures when the Re number is low. However, dispersedly distributed contact areas could remarkably decrease the threshold for the validity of cubic law. That means modifications may still be needed when estimating the hydromechanical behaviour of the very rough rock fractures such as the profiles in the JRC system with large JRC values.

3) Flow simulation

- Generally, the flow rates provided by numerical simulations using FEM by solving Reynolds equation agree well with that obtained from coupled shear-flow tests. Detailed numerical simulation results such as aperture and contact distributions also agree well with the flow images obtained from coupled shear-flow-tracer tests.

- For the unidirectional flow simulations, the flow rate in the fracture increases during shearing process. However, a greater increase is observed in the direction perpendicular to the shear due to the significant flow channels newly created in that direction.

- Non-parabolic velocity profile can occur at large Re numbers, inducing non-Darcy pressure drop, which can be well represented by solving 3-D Navier-Stokes equations but not by solving Reynolds equation. A fast development of non-Darcy pressure drop is observed at Re number from 10 to 50 on a rock fracture with JRC value of 6~8. Quantitatively assessment of the non-Darcy pressure drop requires laboratory tests and numerical simulations on more rock samples with various surface characteristics.

In the present simulations, ignorance of asperity deformation/destruction may be the most significant factor that produced discrepancies between the results of experiments and simulations, which needs a better representation in further numerical models.
Selected References


Li B. and Jiang Y. Experimental study and numerical analysis of shear and flow


