Experimental study on mechanical characteristics and nonlinear flow behaviors of rock fractures during shear process

The coupled hydro-mechanical behavior of rock masses have been considered significantly important in many engineering applications, such as reservoir storage, liquid waste disposal, contaminant containment, oil and nature gas production and geosequestration of greenhouse gasses. Two issues should be considered when evaluating the hydro-mechanical behavior of underground spaces in fractured rock masses: (1) the shear behavior of rock fracture is the key factor that controls the mechanical behaviors of fractured rock mass encountering a rock structure construction; (2) hydraulic behavior, mostly taking place in rock fractures, can alter the mechanical and hydrogeological properties of rock mass, facilitating the particle transport through rock fractures. It is becoming essential to be able to characterize the physical processes governing shear-flow interactions of individual fractures that could be the fundamental elements to understand the coupled hydro-mechanical behavior of rock masses.

First, the shear behavior and AE characteristics of rough-walled fractures were investigated through laboratory experiments by using direct shear test apparatus together with AE system. Constant normal load (CNL) condition as well as a more representative boundary condition for underground rock of constant normal stiffness (CNS) condition were applied to these fractured specimens to evaluate the effect of boundary condition on shear behavior of rock fractures. The results indicated that the post-peak shear stress and dilation show increasing trend with increasing normal stiffness. In addition, asperity damage behavior was evaluated based on acoustic emission (AE) test, and the influence of boundary conditions on asperity damage behavior during shear process was analyzed. The evolution of AEs with the shear displacement can accurately reflect the shear failure mechanism during shear process. The results showed that the AEs were more active under CNS boundary conditions, due to more significant asperity damage induced by the high normal stress. Additionally, the cumulative AE values significantly increase with increasing normal stiffness.

Second, the linear flow characteristics of rough-walled fractures during shear process under different boundary conditions were investigated through laboratory experiments by
using coupled shear-flow test apparatus. A series of shear-flow tests for different rough-walled fractures under various CNS boundary conditions were performed to investigate the effects of surface roughness, normal stiffness and initial normal stress on coupled shear-flow behavior of rock fractures. As indicated by the experiment results, the shear behavior of rough-walled fractures was significantly influenced by the surface roughness, normal stiffness, and initial normal stress. The hydraulic tests show that the evolutions of transmissivity and hydraulic aperture during shear process exhibit a three-stage behavior. The dominant factors for different stages were the aperture of the fracture and contact conditions. Additionally, the hydraulic behavior of rock fracture was also influenced by boundary stress conditions. The transmissivity and hydraulic aperture decreased gradually, as the normal stiffness and initial normal stress increase.

Finally, the nonlinear flow behaviors of rough-walled fractures during shear process were investigated through laboratory experiments and numerical simulations. The coupled shear-flow tests were conducted on different type of rough-walled fractures with different shear displacements under various boundary conditions. The effects of shear process, fracture surface roughness, boundary normal stiffness and initial normal stress on nonlinear flow behaviors are analyzed. The results show that Forchheimer equation provides a good description of the nonlinear relationship between flow rate and pressure gradient in rough-walled fractures. When the Reynolds number increases to the critical Reynolds number, the inertial effects are not negligible. Smaller shear displacement and aperture, larger boundary stress conditions, rougher fracture surfaces and a greater number of contact areas would result in the onset of nonlinear flow at a lower critical Reynolds number. 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 specimen. A Mathematical expression was proposed to quantify the critical Reynolds number using the contact ratio and fractal dimension of the fracture surface based on visualization of shear-flow experiment and 3D laser scanning technique, which can help to choose proper governing equations when solving problems associated with fluid flow in rough-walled fractures. Additionally, to improve the understanding on fluid flow behavior in sheared rock joints in nonlinear regimes, fluid flow simulation solving Navier-Stokes equations with hydraulic gradient spanning ten orders of magnitude is conducted. The results indicate that the nonlinear flow regimes of rock fractures can be significantly influenced by tortuosity of flow paths, which was controlled by local aperture distributions, contact conditions and boundary stress conditions.