Shear Failure and Anchoring Behavior of Discontinuous Fracture Structures in Rock Masses

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Rock masses, as complex geological bodies, have undergone billions of years of geological tectonics, weathering or erosion and thus contains numerous discontinuities such as joints, fissures, fractures, weak interlayers and fault zones. The discontinuities play crucial roles in the stability of rock masses, as their mechanical strength is much lower than that of intact rock. Landslides of rock slopes and instability of underground excavations are often closely related to shear slip of pre-existing discontinuities. The discontinuities in the rock masses present a complex fracture structure, which varies in size, orientation and geometry and dominates the anisotropic behavior of the fractured rock masses. This thesis presents a study on the shear behavior and anchorage effect of two types of discontinuous fracture structures (i.e., planar intermittent fracture structure and en-echelon fracture structure). The main objective is to reveal the failure mechanism of fractured rock masses under shearing and to promote optimal support design for rock engineerings.

First, direct shear tests were conducted on the planar intermittent fracture structure under constant normal load (CNL) conditions. The influence of structure parameters such as persistency, overlapping and spacing, were mainly investigated. And, the shear strength, dilation, shear failure patterns and micro-cracking mechanism of planar intermittent fractures were revealed. The test results showed that shear failure of planar intermittent fractures usually involves multiple coalescence modes of rock bridges, which are greatly affected by structure configurations of fractures and normal stress. The numerical tests revealed that the macro-shear failure of rock bridges is actually dominated by meso-tensile cracking. Under the same normal stress, the shear strength and dilation behavior are mostly dominated by the persistency of fractures, which essentially determines the roughness of the macro-shear fracture surface. Furthermore, the acoustic emission characteristics of planar intermittent fractures were evaluated by the hit rate, energy rate and *b* value. A lower *b* value, indicating a more intense shear failure, is usually related to a smaller persistency and medium spacing.

Second, the en-echelon fracture structure was sheared under constant normal load (CNL) and constant normal stiffness (CNS) conditions. The influence of structural parameters (e.g., fracture angle and persistency) on the shear strength, friction and dilation behavior, shear failure structures, and acoustic emission response was comprehensively evaluated. Two typical shear stages (i.e., cracking stage and shear-slipping stage) are quantitatively described by three shear strength indices and three dilation indices, which present varying degrees of anisotropy under different shear stages and boundary conditions. Also, five types of shear failure structures evolved from en-echelon fractures can be observed. They essentially depend on different crack types and coalescence patterns of rock bridges and greatly affect the friction and dilation characteristics in the shear-slipping stage. Under the CNS conditions, dilation induced by block rotation (for block failure structure) and sawtooth climbing (for sawtooth failure structure) will cause a higher normal stress and thus a higher shear strength. The relationship between normal stiffness and shear strength can be described by an empirical equation. In addition, some potential implications for the rock engineerings such as rock slopes and underground fault system were proposed based on the experimental results. For example, an idealized vertical slope containing en-echelon faults was analyzed. Three safety factors and three critical failure plane angles derived from three shear strength indices were defined and calculated, and they are all related to the structure parameters of faults. The test results were also used to reveal the formation of some typical fault structures in field and provide some new insights into the earthquake mechanisms and stick-slip phenomenas induced by en-echelon faults.

Finally, based on the understanding of the shear failure of two types of discontinuous fracture structures, the anchoring behavior under different bolting schemes and different bolt materials were further investigated. The test results showed that fully encapsulated bolt can greatly improve the shear strength, while end encapsulated bolt behaves better at a larger shear displacement. The deformation and breakage of bolt are found to be closely related to the failure structures of fractures. The shear displacement at bolt breakage tends to be smaller with the decreasing joint persistency. The acoustic emission tests showed that the fully encapsulated rigid bolt noticeably reduced the shear damage, while it increased the shear failure intensity. Then, the anchorage effects of conventional-rigid (CR) bolt and energy-absorbing (EA) bolt were quantitatively compared and evaluated based on shear strength and dilation indices as well as a defined bolt contribution index. The test results show that the anchorage effect of bolt is closely related to the bolt material and fracture angle. This is essentially determined by the bolt deformation mechanism that varys in different shear failure structures. Based on the test results, a deformation factor was proposed to evaluate the deformation performance of bolt and to predict the bolt breakage at different fracture angles. This part provides great insights into the design of bolt support for jointed rock masses.