Review Article

Research Progress on Shear Characteristics of Rock Joints under Constant Normal Stiffness Boundary Conditions

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The constant normal stiffness (CNS) boundary condition is more representative for the underground engineering, in which the shear-induced dilation is restricted by surrounding rocks, resulting in an increase in the normal stress. Therefore, the use of CNS boundary conditions in the research of shear-slip failure of underground rock engineering is more in line with the actual situation. Taking the instability and failure of surrounding rock in underground engineering as the background, the present study introduces the engineering background of CNS boundary conditions and the research progress on shear characteristics of rock joints under CNS boundary conditions. Three key directions for future research are proposed based on the latest research results of shear characteristics of rock joint under CNS boundary conditions: ① developing a rock joint shear test system that can realize the function of “CNS boundary conditions + shear-seepage test + visualization”; ② carrying out the shear tests of real rock joints under CNS boundary conditions based on 3D scanning and 3D carving technology; and ③ carrying out the shear tests of rock joint network under CNS boundary conditions.

1. Introduction

The stability of the rock mass is related to the construction, operation, and maintenance of important basic industrial content such as mining resources, transportation, water conservancy and hydropower, and national defense engineering [1–3].

However, the structural planes are widely presented in engineering rock masses which are formed by joints, cracks, and weak interlayers. The weak planes greatly weaken the strength and stability of the rock mass [4, 5]. For the surrounding rock of deep underground engineering, the rock mass will undergo shear failure along the structural plane under the action of tectonic stress and seismic load. The shear-slip movement of the rock mass further weakens the bearing capacity and mechanical properties of the rock mass, thereby inducing serious roof deformation and collapse [6–10].

In addition to the lack of support measures in some projects, the most important reason for the shear slip of underground engineering rock mass is that the shearing effect of the structural plane is controlled by the complex geological environment and its own structural characteristics [11, 12]. A unified understanding has not yet been formed academically due to the following reasons. First, the structural characteristics of the joint are one of the decisive factors affecting the shear characteristics of the joint while the previous studies mainly focused on single joints but lacked in-depth discussion on the shear characteristics of complex joint network structures [13, 14]. Second, most scholars currently use similar materials (high-strength cement, gypsum, and so on) to replicate natural joints while there are still big differences between samples poured with similar materials and natural rocks in terms of brittleness and mechanical properties. In addition, the constant normal load (CNL) boundary condition is still used in a large

number of studies on the shear-slip problems of deep underground engineering, which leads to overestimation of the dilatancy of joints. For the case of deep underground, constant normal stiffness (CNS) boundary conditions are more applicable than CNL because the normal stress that is applied perpendicular to the shear direction is not a constant value [8, 15–19], while determined by the stiffness of surrounding rock (Figure 1).

The present study concludes the future research direction of shear characteristics of rock joints under CNS boundary conditions by summarizing and analyzing the research progress in four aspects: CNS testing machine, roughness characterization of structural plane, shear strength of rock joints under CNL boundary conditions, and shear behavior of rock joints under CNS boundary conditions. The research results will provide reference for the follow-up research.

2. Research Status of Shear Behavior of Rock Joints

Since the 1960s, the shear characteristics of joint planes began to receive attention and research from scholars because the engineering geological disasters caused by the shear slip of joint surface are constantly emerging. Previous research results show that the key factors affecting the shear strength of joint surface mainly include two aspects: one is internal factors, including rough undulation characteristics of joint surface, filling characteristics, and mechanical properties of joint surface; the other is the external factors, such as the stress state of the joint surface and the boundary conditions. This paper focuses on the development trend of the shear behavior of rock joints under the CNS boundary conditions. Therefore, the research and development status of the CNS testing machine, the characterization of structural surface roughness, the shear strength of rock joints under the CNL boundary conditions, and the shear behavior of rock joints under the CNS boundary conditions are listed in detail.

2.1. Research Progress of CNS Testing Machine. In 1985, Indraratna et al. [20–22] developed a set of equipment that can conduct the shear test of rock joints under CNS boundary conditions at the University of Wollongong, Australia (Figure 2(a)). The shear testing machine uses a set of springs to simulate the normal stiffness of the surrounding rock, and the normal stiffness is 8.5 kN/mm, which can be adjusted by replacing the springs.

In 2000, Jiang et al. [17, 23, 24] of Nagasaki University in Japan developed a new type of servo-controlled shearing instrument using automated numerical control technology and virtual instruments (Figure 2(b)). Compared with the previous CNS shearing instrument, the advantages of this testing machine lie in the following three aspects: first, it improves the accuracy of the test results; second, the change of the normal stiffness no longer requires cumbersome replacement the spring, which can be set through computer input; third, the test plan can be adjusted at any time; for example, the boundary conditions of CNL and CNS can be switched at will during the shear test. In 2006, Jiang et al.

[6, 14, 26] of Nagasaki University in Japan improved the previous equipment and developed a shear-seepage testing machine for rock joints. The testing machine realizes the coupling test of shear and seepage of rock joint under the boundary conditions of CNL and CNS. The testing machine is mainly composed of electro-hydraulic servo system unit, load and displacement measurement and control unit, shear loading unit, water supply, sealing and measuring device, and visualization system equipment. In 2008, Zhang et al. of Tsinghua University in China developed a large-scale three-dimensional soil-structure interface testing machine [27]. The testing machine has the advantages of high loading capacity and large cross section. The testing machine can provide CNL, constant normal displacement, CNS, and other boundary conditions through the servo control system. In 2008, Belem et al. [28–30] at the University of Quebec in Canada developed a servo-controlled shearing instrument. The testing machine not only realizes the shear test under different boundary conditions (CNL, CNS, and constant normal displacement) but also realizes the cyclic shear test of rock joints. In 2018, Gui et al. [25] of Tongji University in China developed a novel multifunctional shear-flow coupled test system for rock joints (Figure 2(c)). The developed test system can carry out the shear-seepage test of rock joints under CNL, CNS, and constant normal displacement boundary conditions.

2.2. Research Progress on Characterization of Structural Surface Roughness. The evaluation of structural surface roughness is the basis for studying joint shear behavior. The rapid and accurate quantitative evaluation of the roughness of structural surface is conducive to the evaluation of shear strength of structural plane and provides scientific basis for the stability evaluation of engineering rock mass in the follow-up and finally serves the engineering practice. Myers [31] proposed the concept of Z2 and gave the corresponding calculation formula to quantitatively describe the roughness of the structural surface (Equation (1)). Mandelbrot [32] calculated the fractal dimension based on fractal theory to evaluate the joint roughness coefficient (JRC). Barton and Choubey [33] proposed 10 standard contour lines for structural surfaces and stipulated that the value range of JRC is 0–20. Sayles and Thomas [34] proposed the structure function SF (Equation (2)); EI-Soudani [35] proposed the ratio of the true length of the fracture surface to its projected length (Equation (3)). Subsequently, scholars established corresponding formulas for calculating JRC based on the abovementioned statistical parameters of joint contours [36, 37] (Equations (4) and (5)). In addition, Xie et al. [38] proposed the empirical relationship between contour fractal dimension and JRC. Du et al. [39] summarized the anisotropy, heterogeneity, nonuniformity, and size effect characteristics of joint roughness coefficients based on extensive investigation of joint surface morphology and perfected the comprehensive evaluation method of joint shear strength. Liu et al. [40] found that JRC of rock joints could not be accurately estimated by using only a single statistical parameter and put forward a classified and weighted fitting

FIGURE 1: Joint shear-slip failure in deep underground engineering. (a) Coal mine roof deformation. (b) Roadway roof shear failure. (c) Joint CNS shearing.

FIGURE 2: CNS shearing instrument. (a) CNS shearing instrument of Wollongong University, Australia [20–22]. (b) CNS shearing instrument of Nagasaki University, Japan [17, 23, 24]. (c) A novel multifunctional shear-flow coupled test system for rock joints of Tongji University [25].

formula to estimate the JRC (Equations (6)). The above research has important guiding significance for the study of joint shear behavior.

$$Z_2 = \left[\frac{1}{L} \int_{x=0}^{x=L} \left(\frac{dy}{dx} \right)^2 dx \right]^{1/2} = \left[\frac{1}{L} \sum_{i=1}^{n-1} \frac{(y_{i+1} - y_i)^2}{x_{i+1} - x_i} \right]^{1/2}, \quad (1)$$

$$SF = \frac{1}{L} \sum_{i=1}^{n-1} (y_{i+1} - y_i)^2 (x_{i+1} - x_i), \quad (2)$$

$$R_p = \frac{1}{L} \sum_{i=1}^{n-1} \left[(x_{i+1} - x_i)^2 + (y_{i+1} - y_i)^2 \right]^{1/2}, \quad (3)$$

$$JRC = 32.2 + 32.47 \log Z_2, \quad (4)$$

$$JRC = 37.28 + 16.58 \log SF, \quad (5)$$

$$JRC = 16.09 \log Z_2^{1st} + 12.70 \log Z_2^{2nd} + 33.75, \quad (6)$$

where x_i and z_i represent the coordinates of the joint surface profile and M is the number of sampling points along the length of a joint surface.

2.3. Research Progress on Shear Strength of Rock Joints under CNL Boundary Conditions. The shear effect of rock joints under CNL boundary conditions has been fully studied and developed for a long time since CNL boundary conditions are easy to implement in the laboratory. In 1966, Patton [41] proposed a bilinear model based on the shear test of regular zigzag joints, the model explaining the control effect of structural surface morphology on its shear strength. Since then, many scholars have carried out research on the shear strength model of the joint surface to serve engineering practice, i.e., Jaeger [3] proposed the shear effect model; Barton and Choubey [33] proposed the JRC-JCS model on the basis of summarizing a large number of tests to estimate the shear strength of structural plane under arbitrary normal stress (Equation (7)); Zhao et al. [42] considered that JMC had an effect on the peak shear stress of joints and proposed the JRC-JMC model (Equation (8)); Grasselli et al. [43] proposed the Grasselli model in three-dimensional scale; Wang et al. [44] proposed a shear strength model of rough structural plane considering shear rate based on the test results and JRC-JCS model (Equation (9)). In addition, Nagayama [45] et al., Li et al., [46], and Liu et al. [40] studied the influence of roughness, joint spacing, joint dip angle, and shear directivity on the shear mechanical properties of rock

FIGURE 3: Specimens of latest studies. (a) Specimens of Han et al. 2020 [48]. (b) Specimens of Huang et al. 2021 [49]. (c) Specimens of Yin et al. 2021 [50].

joint and proposed the corresponding shear strength models.

$$\tau = \sigma_n \tan \left[\text{JRClog} \left(\frac{\text{JCS}}{\sigma_n} \right) + \phi_b \right], \quad (7)$$

$$\tau = \sigma_n \tan \left[\text{JRC} \cdot \text{JMC} \cdot \log_{10} \left(\frac{\text{JCS}}{\sigma_n} \right) + \phi_r \right], \quad (8)$$

$$\tau = 0.982 \sigma_n \tan \left[4.970 (\text{JRC})^{0.475} \log \left(\frac{\text{JCS}}{\sigma_n} \right) + \phi_b \right] \times v^{-0.06}, \quad (9)$$

where σ_n , JCS, ϕ_b (ϕ_r), and v represent the normal stress, joint compressive strength, basic friction angle, and shear velocity, respectively.

2.4. Research Progress on Shear Behavior of Rock Joints under CNS Boundary Conditions. Indraratna et al. [20, 47] first developed a CNS testing machine and proposed an equation suitable for predicting the shear stress of regular serrated joints based on the energy conservation equation and Fourier series. Jiang et al. [24] developed a new type of servo-controlled shearing instrument using automated numerical control technology and virtual control technology and revealed the shear strength, volume expansion mechanism, and energy change law of different rough joint surfaces in the shearing process of rock joints through laboratory experiments. Then, Jiang et al. [17] developed a shear-seepage testing machine for rock joints under the CNS boundary conditions and carried out the relevant research on the hydraulic coupling characteristics in the shear process. In addition, the shear behavior of joints under CNS boundary conditions has been further studied and developed with the

support of the abovementioned equipment. For example, Han et al. [48] carried out a cyclic shear test of rough joints under CNS boundary conditions and revealed the characteristics of joints such as shear stress, dilatancy, surface wear, and acoustic emission response (Figure 3(a)); Huang et al. [49] studied the mechanical behaviors of artificial samples containing multiple parallel joints during shearing under CNS conditions (Figure 3(b)); Yin et al. [50] studied shear mechanical responses of sandstone exposed to high temperature under CNS boundary conditions (Figure 3(c)).

3. Discussion and Conclusion

The development of the CNS testing machine can be roughly divided into three stages. First stage: the testing machine uses springs to simulate the stiffness of the surrounding rock. The above type of testing machine first realizes CNS boundary conditions, while the disadvantages are that the test accuracy is low and the normal stiffness of the test machine is inconvenient to adjust. Second stage: the testing machine uses a servo to control the normal stiffness, which is a revolutionary innovation compared with the first stage. This type of testing machine no longer uses springs to simulate the stiffness of the surrounding rock but develops a computer real-time feedback system to achieve real-time control of the normal stiffness of the testing machine by the computer. Third stage is the shear-seepage coupling test system. This type of testing machine realizes model testing under more complex conditions. The principle of the third stage testing system is to add a seepage system and a visualization system to the second stage testing machine.

Analyzing the research progress of structural surface roughness characterization, it can be found that there are few studies on the use of 3D scanning and 3D carving technology to replicate the original rock structural surface, especially the

research on applying 3D scanning and 3D carving technology to the shear failure of surrounding rock in deep rock engineering is very rare.

Through the analysis of the research progress of rock joint shear strength under CNL boundary conditions, it can be found that most of the current studies are based on the simplification of joint surface morphology and stress state and do not consider the influence of real joint surface characteristics and the influence of surrounding rock on joint deformation. Therefore, the shear strength prediction model of joints under CNL boundary conditions is only suitable for shallow buried engineering or rock slope engineering without bolt.

In terms of the shear behavior of rock joints under CNS boundary conditions, the previous studies have reflected the shear mechanical properties of rock joints under CNS boundary conditions, including shear strength, dilatancy, joint surface damage, and so on. However, most of the research studies on rock joint shear under CNS boundary conditions are limited to the study of a single joint or the use of similar materials for model pouring. In addition, most of the joints are regular serrated joints. It is worth noting that there are two problems in the above research: one is that joints do not exist in isolation in rock mass, and they are often widely distributed in rock mass in the form of network; the other is that the model poured with similar materials is quite different from natural rock in brittleness and mechanical properties.

Based on the research progress of shear behavior of rock joints under CNS boundary conditions, three important directions for future research are proposed: ① developing a rock joint shear test system that can realize the function of “CNS boundary conditions + shear-seepage test + visualization”; ② carrying out the shear tests of real rock joints under CNS boundary conditions based on 3D scanning and 3D carving technology; and ③ carrying out the shear tests of rock joint network under CNS boundary conditions.

Conflicts of Interest

The author(s) declare that there are no conflicts of interest regarding the publication of this article.

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