Experimental and numerical modeling study of rock joint mechanical properties and failure mechanisms under cyclic shear

ZHANG Maochu1,2, SHENG Qian1,2, CUI Zhen1,2*

1State Key Laboratory of Geomechanics and Geotechnical Engineering, Institute of Rock and Soil Mechanics, Chinese Academy of Sciences, Wuhan, Hubei 430071, China.
2School of Engineering Science, University of Chinese Academy of Sciences, Beijing, 10049, China.

Email: zhangmaochu17@mails.ucas.ac.cn; zcui@whrsm.ac.cn

Abstract. Cyclic loading is a common concept in geotechnical engineering, which has an important effect on rock joints. To study the mechanical properties and failure mechanisms of rock joints under cyclic loading, a kind of rock joint cyclic shear device with a top-to-top configuration is proposed in this work. Cyclic shear tests of rock joints are carried out with the cyclic shear equipment. With three-dimensional texture scanning technology, the cyclic shear failure mode of the rock joint is analyzed. The variation trends of shear strength and stiffness of the rock joint under the combined action of normal stress, joint roughness, shear rate, and cyclic shear number are studied. The results show that the normal stress and the roughness are positively related to the cyclic shear strength of the rock joint. With the increase of shear rate and number of cycles, the shear strength and stiffness of the rock joints decrease gradually. In the first cycle of the shear process, the peak shear strength and stiffness of the rock joints reach the maximum values. After the second cycle, the peak shear strength and stiffness of the rock joints decrease slightly and tend toward a constant value under the same normal stress. Observation of the sheared rock joint surface reveals that sliding and shearing damage to the protrusions occurred during the cyclic shear process. Under the combined action of the normal stress, joint roughness, shear rate, and cyclic shear number, the protrusions would slide while moving up to a different height until they are eventually sheared off. In the next cyclic shear process, the friction and shear damage of the residual protrusions continues to occur. With the increase of the number of cyclic shear processes, the wear on the residual protrusions gradually decreases and stabilizes. Finally, the numerical cyclic shear test of the rock joint is performed with the discrete element method (DEM) code 3DEC. A good comparison is found between laboratory data and DEM results.

1. Introduction
A rock mass is composed of joints and blocks cut by those joints. Under the conditions of earthquakes [1], water level rise and fall in reservoirs, [2] or mining of coal seam working faces [3], rock joints are subjected to cyclic loading. Cyclic loading weakens the strength of rock joints, leading to the dislocation of rock masses along the joint and, thus, causing damage to underground engineering. Therefore, it is of great significance to study the mechanical properties of rock joints under cyclic loading.
Many scholars have carried out researches on cyclic shear mechanical properties of rock joints. They have studied the shear mechanical behavior of natural rock mass discontinuities (or artificial rock mass discontinuities) under cyclic loading. Based on the results of cyclic shear mechanical properties studies, many valuable constitutive models have also been proposed. Souley et al. presented an extension of the Saeb and Amadei model to take into account joint loading and unloading in both normal and shear directions. Belem et al. proposed two rock joint surface roughness degradation models to predict the variation of joint surface degradation during shearing under both constant normal load and constant normal stiffness loading methods. Lee et al. proposed an elastoplastic constitutive model based on the experimental results of rock joints under cyclic shear loading. Their model can consider the degradation of second-order asperities. Previous studies have considered various factors affecting rock joint shear, but the interactions of these factors have been less considered. How these properties affect rock joint behavior under cyclic shear loading is lacking systematic consideration. In addition, numerical simulation is an effective method to study the mechanical response and stability of rock masses under cyclic loading. The selection of a constitutive model is vital for the accuracy of the simulation result.

Many joint models have been applied in rock discontinuity numerical simulation. Cundall et al. used the continuously yielding model (CY model) to solve the sliding problem of discontinuity in practical projects. Gao et al. performed numerical direct shear tests for joints with the CY model. Cui et al. introduced a modification to Cundall’s CY through comparison with existing experimental data. In most studies, the CY model is used to simulate unidirectional shear of rock joints. This work focuses on the mechanical properties and failure mechanisms of rock joints under cyclic shear. A kind of rock joint cyclic shear device with a top-to-top configuration is proposed in this work. Cyclic shear tests of rock joints are carried out with the cyclic shear equipment. With 3D texture scanning technology, the cyclic shear failure mode of the rock joint is analyzed. Finally, a numerical model of the rock joint is established with the DEM program 3DEC and a numerical shear test is carried out. Based on the obtained numerical result, the performance of the CY model in representing the cyclic shear mechanical behavior of the rock joint is evaluated.

### 2. Experimental program

#### 2.1. Rock joint cyclic shear device (RJCS-600)

![Figure 1. The multifunctional circulating shearing device for rock joints.](image)

The cyclic shear tests are performed by the rock joint cyclic shear device. As shown in Figure 1, the device is composed of three parts: test structure, control and acquisition system, and power system. In the test structure, a top-to-top configuration is designed to fix the upper half of the shear box and provide load power to the lower half of the shear box. The top-to-top configuration is a structural design that uses two jacks opposite each other to hold the shear box. A hydraulic station is the power unit of the system, which provides the execution power for the test mechanism. The control box is responsible for signal acquisition and processing. The software is responsible for running specialized control programs. Operator–machine instruction interaction, algorithmic control, and data storage are carried out by the software.
A schematic of the RJCS-600 test structure is shown in Figure 2. The prepared rock joint sample is put into the upper and lower halves of the shear box (1). The front and back of the sample should be consistent with the shear box, and the rock joint sample is guaranteed to be located in the reserved space between the upper and lower halves of the shear box. After starting the motor and running the software, the normal hydraulic jack (2) is first extended to contact the sample. Then we set the normal stress in the normal loading parameter setting, and start the normal loading. The locking hydraulic jack (3) is extended to the left of the upper shear box, and the locking pressure slowly increases to the required locking pressure value, which is generally set at 250 kN. The two tangential hydraulic jacks (4) and (5) are set to tighten mode and are extended so that the lower shear box is clamped. Control parameters such as forward and reverse cyclic shear rate and times required by the tests are set, and the data acquisition button is engaged to start the cyclic shear. The cyclic shear test is automatically executed. The number of cyclic shear processes is set in the Auxilary Parameters settings in the software, and the test will automatically stop when the number of cycles is reached. At the end of the test, data recording stops, the locking hydraulic jack is retracted first, then the normal hydraulic jack, and the tangential hydraulic jacks are loosened. The pressure is released to shut down, then the sample and residue are removed, and finally the power is turned off.

2.2. Test sample preparation
Shear tests on rock joints are usually destructive tests. The shear properties of natural rock joint samples or joint samples of intact rock are split and gouged and cannot be studied again under different test conditions once they are shear damaged. For rock joint samples, artificial samples are more convenient to produce compared with natural rock masses, and the roughness of the rock joint is controllable. A large number of parallel tests can be conducted to explore the influence of a single factor variable or multiple factor variables on the shear strength characteristics of the rock joint. Therefore, in this work, samples of rock joints are mass produced by using similar materials for cyclic shear tests. All the samples are molded using a special kind of concrete and a special 3D-printed resin plate. In practical engineering, the mechanical parameters of rock mass are usually determined according to the classification of rock mass quality. Referring to the relevant specifications [14], similar materials are prepared according to the surrounding rock mass of grade IV, and the uniaxial compressive strength of the samples is 21.1 MPa. To investigate the effect of roughness, two kind of rock joint samples are prepared, named group A and group C respectively. The preparation process of rock joint sample is shown in Figure 3.

Figure 2. Schematic of the test structure: 1, shear box; 2, normal loading cylinder; 3, locking hydraulic jack; 4, forward shear cylinder; 5, reverse shear cylinder; 6, normal load force transducer; 7, forward shear force sensors; 8, reverse shear force sensors; 9, linear variable differential transformer (LVDT) sensor for normal displacement; 10, LVDT sensor for tangential displacement.
2.3. Testing program

Many sets of cyclic shear tests with various shear rates and normal stresses were conducted on artificial rock joints under constant normal load conditions. Three tests with different normal stress levels were conducted, i.e., 1.0 MPa, 3.0 MPa, and 5.0 MPa. Cyclic loading direct shear tests with shear rates of 1.2 mm/min, 1.8 mm/min, and 2.4 mm/min are conducted on the samples. The tests under various shear rates are continued for five shear cycles.

3. Results for rock joint samples under cyclic shear tests

3.1. The effect of normal stress

![Figure 4](image)

**Figure 4.** The first cycle shear curve of rock joints under different normal stresses.

Figure 4 shows a comparison between the cyclic shear behavior of joints at low shear rate (1.2 mm/min) under 1 MPa, 3 MPa, and 5 MPa normal stresses. In the first cycle, the high normal stress–shear curve is higher than the low normal stress–shear curve. The influence of normal stress on the cyclic shear curve can be summarized as follows. With the increase of normal stress, the shear strength of the rock joint increases continuously and the slope (shear stiffness) of the first and third quadrant curve increases with the increase of normal stress.

3.2. The effect of roughness

![Figure 5](image)

**Figure 5.** The shear strength changes for different roughnesses of rock joints.
Rock joint samples with two roughness levels are set up in the test, and the roughness index is characterized by the 3D roughness coefficient $R_s$ of the joint surface proposed by Belem et al.\cite{15}. Based on the 3D point cloud data of the two kinds of rock joint, the roughness coefficient values of $R_s = 1.0424$ for group A specimens and $R_s = 1.0722$ for group C specimens are calculated. The roughness of group C joint specimens is higher. The results of the cyclic shear test (Figure 5) show that the shear strength is also relatively higher for joint surfaces with higher roughness (Group C specimens) at the same normal stress. At lower normal stresses, the peak strength in the first shear cycle varies greatly due to the difference in roughness. As the normal stress increases, the effect of joint surface roughness on its shear strength diminishes, and the gap in sample shear strengths with different roughness values continues to narrow with the increase in the number of cyclic shear processes.

3.3. The effect of shear rate

![Figure 6](image_url)

Figure 6. Variations in shear strength of rock joints at different shear rates.

To study the effect of shear rate on shear deformation and strength, the normal stress is controlled as 3 MPa, and the cyclic shear tests are conducted at the shear rates of 1.2 mm/min, 1.8 mm/min, and 2.4 mm/min, respectively. The cyclic shear results are shown in Figure 6. It can be seen that the shear strength of the rock joint decreases with the increase of the shear rate by comparing the curves. At the higher shear rate (2.4 mm/min), the difference between the strengths of subsequent cycles keeps decreasing.

3.4. The effect of the number of cycles

![Figure 7](image_url)

Figure 7. The shear strength of the rock joint varies with the number of cycles.

The peak stress of forward shear in the first cyclic shear is selected as the shear strength of the rock joint. The results of the shear strength of the rock joint vary with the number of cyclic shear processes, as shown in Figure 7. It can be seen that the shear strength of the rock joints gradually decreases with the increase in the number of cycles. The strength drop is larger from the first to the second cycle, which reaches 7.8% on average. The higher the normal stress, the greater the strength drop (6.7% for 1 MPa, 7.8% for 3 MPa, and 9.0% for 5 MPa). In subsequent shear cycles, the strength decreases slowly.
The normal displacement gradually decreased with the increasing number of cycles on the rock joint. Under the condition of low normal stress, the decrease of normal displacement tends to stop after the fourth round of cyclic shear. However, under the condition of high normal stress, the normal displacement continues to decrease after the 4th round of cyclic shear.

3.5. The variation of peak shear stiffness

The shear stiffness of the rock joint is determined based on the shear displacement $u$ (peak) which is required to reach the peak shear strength. The shear stiffness is an extremely important parameter in the numerical calculation considering contact element [16]. The value of the shear stiffness is determined according to equation (1) based on the shear stress–shear displacement curve of the rock joint specimen.

$$k_s = \frac{\tau_p}{u_p} \quad (1)$$

Where $k_s$ is the peak shear stiffness, $\tau_p$ is the peak shear strength, and $u_p$ is the shear displacement corresponding to the peak shear strength.

| Specimen type | $\sigma_n$(MPa) | $N_c$(times) | $\tau$(MPa) | $k_s$(MPa/mm) |
|---------------|-----------------|--------------|-------------|---------------|
| A1 1          | 1.93            | 0.33         |             |               |
| A1 2          | 1.80            | 0.30         |             |               |
| A1 3          | 1.72            | 0.29         |             |               |
|               | 1.68            | 0.28         |             |               |
|               | 1.65            | 0.28         |             |               |
|               | 3.59            | 2.56         |             |               |
|               | 3.31            | 0.58         |             |               |
| A2 3          | 3.27            | 0.58         |             |               |
|               | 3.29            | 0.56         |             |               |
|               | 3.29            | 0.56         |             |               |
|               | 5.47            | 3.28         |             |               |
|               | 4.98            | 1.24         |             |               |
| A3 5          | 4.93            | 0.86         |             |               |
|               | 4.94            | 0.84         |             |               |
|               | 4.93            | 0.84         |             |               |
|               | 2.15            | 1.41         |             |               |
|               | 1.83            | 0.30         |             |               |
| C1 1          | 1.74            | 0.29         |             |               |
|               | 1.71            | 0.28         |             |               |
|               | 1.68            | 0.28         |             |               |
|               | 3.96            | 3.00         |             |               |
|               | 3.17            | 0.53         |             |               |
| C2 3          | 3.15            | 0.55         |             |               |
|               | 3.07            | 0.52         |             |               |
|               | 3.05            | 0.51         |             |               |
|               | 5.86            | 3.43         |             |               |
|               | 5.07            | 0.84         |             |               |
| C3 5          | 5.08            | 0.84         |             |               |
|               | 5.13            | 0.85         |             |               |
|               | 5.12            | 0.85         |             |               |

The peak shear stiffness of the rock joints is calculated and listed in Table 1. Figure 8 shows the variation of the peak shear stiffness of the rock joint with the number of cycles for each normal stress value. As can be seen from Figure 8, the peak shear stiffness of the rock joints decreases continuously with increasing numbers of cycles. When the normal stress is low (1 MPa) and the roughness of the joint is small, the shear curve in the first cycle shows ductile damage characteristics. With the increase of shear displacement, the shear stress also increases. After shearing to a certain displacement, the increase of the shear stress slows down and no obvious peak shear strength appears which is similar to the second
cycle in behavior. The result indicates that the degradation of roughness will lead to the transformation of the shear curve from brittle (with obvious peak strength) to ductile (without obvious peak strength).

![Graph showing peak shear stiffness versus number of cyclic shear processes for rock joint samples.](image)

**Figure 8.** The peak shear stiffness versus number of cyclic shear processes for rock joint samples.

### 3.6. The damage mode of rock joints under cyclic shear

![EinScan-Pro 3D scanner](image)

**Figure 9.** EinScan-Pro 3D scanner

![3D texture scan images of rock joint surfaces before and after cyclic shear test](image)

**Figure 10.** 3D texture scan images of rock joint surfaces before and after cyclic shear test

To investigate the damage mechanism of the rock joints under cyclic shear loading, a 3D texture scanner (EinScan-Pro 3D) is installed. Three-dimensional texture scans of the rock joint surface before and after the test are performed. To improve the scanning accuracy, the rock joint is fixed and scanned using a rotary table with a single slice accuracy of 0.05 mm, as shown in Figure 9. Figure 10 shows images of the joint surfaces obtained by 3D texture scanning, presented as 3D data. As shown in Figure 10, the scuff mark and shear-off characteristics of the joint surface under cyclic loading can be clearly revealed. From the analysis of the observed damage characteristics, it is concluded that the slip friction and shear-off damage of the joint surface occur simultaneously in the cyclic shear process.

The shear strength–shear deformation curve and normal displacement–tangential displacement curve are reflections of the deformation and damage of the joint surface in the shear process. The deformation and damage characteristics of the joint surface in the cyclic shear process occur gradually with the
deformation of the convex feature on the joint surface. Under the combined effect of various influencing factors, the convex feature slips to different heights and then breaks. The unbroken part of the convex feature continues to assume the slip friction effect. In the next cycle, the residual convex body continues to undergo frictional slip and shear. The shear strength gradually decreases throughout the cyclic shear process, finally stabilizing after five–six cycles in this study. At the same time, the wear on the residual protrusions gradually decreases and stabilizes as the number of cycles of shearing increases. At higher normal stresses, the convex feature is destroyed during cyclic shear, but no large expansion phenomenon is observed. In the first cyclic shear, most of the microscale protrusions are sheared off and; therefore, the maximum shear strength is observed.

4. Numerical simulation test of rock joints under cyclic shear load

4.1. The numerical test model

3DEC is a 3D numerical program. The numerical program is based on the discrete element method (DEM), proposed by Cundall in 1971. DEM is widely used to describe the mechanical behavior of discontinuous media, represented as an assemblage of discrete blocks. In this work, 3DEC is used to perform the numerical simulation tests of rock joints under cyclic shear. The laboratory cyclic shear tests are taken as a reference to the numerical results.

Figure 11. The model for the numerical cyclic shear tests.

Figure 11 shows the DEM model constructed in the 3DEC program. The sample is divided into upper and lower parts by rock joint in laboratory test. In the model, the upper block represents the block in the upper shear box and the lower block represents the block in the lower shear box. The size of the numerical model is consistent with the samples used in the laboratory tests. In this work, the constitutive model of the rock block follows a perfect elastoplastic model. The CY model is adopted as the constitutive model of rock joint. The CY model is considered more realistic than the standard Mohr-Coulomb model in that the CY model attempts to account for some nonlinear behaviors observed in physical tests, such as joint shearing damage. From the experimental results of rock joint cyclic shearing, the shear curves also present nonlinear characteristics. Therefore, the CY model is adopted to explore the realization method of cyclic shearing numerical tests on the rock joints. The process of the numerical simulation tests is consistent with that of the laboratory tests to facilitate comparison of the tests. In the numerical test, the lower block is fixed and the upper block shears from left to right. The loading rate is set to 0.02 mm/step. The normal stress is set to 1.0 MPa. The model parameters in the numerical shear tests are listed in Table 2.

| Type   | Density (kg/m³) | Bulk modulus (GPa) | Shear modulus (GPa) |
|--------|----------------|--------------------|---------------------|
| Block  | 2300           | 2.79               | 2.10                |
4.2. The numerical test results

Figure 12. Comparison of laboratory test results and numerical model results of rock joints under cyclic shear

Figure 12 shows a comparison between the laboratory test result and DEM result. It can be seen that the curve of the numerical simulation is basically consistent with the test result. The CY model is suitable for representing the nonlinear characteristics of the rock joint cyclic shear curve. For the cyclic shear curve, the rising stage before the peak and the descending stages in the first and third quadrants all are satisfactorily captured by the CY model. The simulated shear strength has little deviation from the test result. Subsequent work will further use DEM and the CY model to conduct in-depth research on rock joint cyclic shear numerical tests, explore the influence of factors such as shear rate and contact parameter values, and obtain more results.

5. Conclusion
The results of experimental and numerical studies on the mechanical properties and failure mechanism of rock joints under cyclic shear are as follows:
(1) Using the developed cyclic shear system, cyclic shear tests are carried out on rock joints to study the changes in shear deformation and strength of joints under different conditions of normal stress, contact surface roughness, shear rate, and number of cycles. The mechanical properties and damage characteristics of the rock joints under cyclic loading are analyzed.
(2) The normal stress, roughness, shear rate, and cyclic shear number all have significant influences on the cyclic shear deformation and strength of the rock joint. Under the combined action of the four factors, the convex feature slips to different joint surface heights and then breaks, while the uncut part continues to bear the frictional effect of slip. In the next cycle, the residual convex feature continues to undergo frictional slip and shear. The shear strength gradually decreases with the increase in the number of shear cycles. The wear on the residual convex feature gradually decreases and the shear strength tends to become constant.
(3) The shear characteristic information of the joint surfaces was scanned by the texture camera of the 3D scanner. The shear scratches on the joint surfaces can be clearly seen from the 3D texture image. The shear damage characteristics of the joint surfaces are also identified through comparative analysis, which play an important auxiliary role in the study of joint damage mechanisms.
(4) Based on the 3DEC program, numerical simulated cyclic shear tests of rock joints are carried out. A good comparison is found between the laboratory data and DEM results. This indicates that the application of the CY model is reasonable for representing the cyclic shear mechanical behavior of rock joints.

Acknowledgments
This work is supported by the National Natural Science Foundation of China (Grant nos.: 51779253 and 52079133). This work is also a major project of the Key Laboratory for Geomechanics and Deep Underground Engineering, China University of Mining & Technology (Grant no.: SKLGDEUEK1912), and the Youth Innovation Promotion Association of the Chinese Academy of Science.
References

[1] Li H B, Feng H P, Liu B. (2006) Study on strength behaviors of rock joints under different shearing deformation velocities. Chinese Journal of Rock Mechanics and Engineering, 25(12): 2435-2440.

[2] Ni W D, Liu X, Xia H. (2013) Research on dynamic stability of reservoir slope based on water weakening effect. Yangtze River, 44(23): 55-59.

[3] Zhang Z Y, Zhong C L, Xue K S, et al. (2021) Mechanical mechanism of pore fluid on coal dynamic disasters under cyclic loading. Journal of China Coal Society, 46(2): 466-476.

[4] Homand F, Belem T, Souley M. (2001) Friction and degradation of rock joint surfaces under shear loads. International Journal for Numerical and Analytical Methods in Geomechanics, 25(10): 973-999.

[5] Liu B, Li H B, Liu Y Q. (2013) Experimental study of deformation behaviour of rock joints under cyclic shear loading. Rock and Soil Mechanics, 34(9): 2475-2488.

[6] Mirzaghorbanali A, Nemcik J, Aziz N. (2014) Effects of shear rate on cyclic loading shear behaviour of rock joints under constant normal stiffness conditions. Rock Engineering, 47(2): 1931-1938.

[7] Souley M, Homand F, Amadei B. (1995) An extension to the saeb and amadei constitutive model for rock joints to include cyclic loading paths. International Journal of Rock Mechanics and Mining Sciences & Geomech Abstract, 2(32): 101-109.

[8] Belem T, Souley M, Homand F. (2007) Modeling surface roughness degradation of rock joint wall during monotonic and cyclic shearing. Acta Geotechnica, 2: 227-248.

[9] Lee H S, Park Y J, Cho T F, et al. (2001) Influence of asperity degradation on the mechanical behaviour of rough rock joints under cyclic shear loading. International Journal of Rock Mechanics and Mining Sciences, 38(7): 967-980.

[10] Cundall P A, Lemos J V. (1990) Numerical simulation of fault instabilities with a continuously yielding joint model. In: Fairhurst (ed) Rockbursts and seismicity in mines. Balkema, Rotterdam, 147-152.

[11] Cui Z, Sheng Q, Leng X L. (2018) Effects of a controlling geological discontinuity on the seismic stability of underground caverns subjected to near-fault ground motions. Bulletin of Engineering Geology and the Environment, 70(1): 265-282.

[12] Cui Z, Sheng Q, Leng X L. (2019) Estimation of the mechanical properties of igneous rocks in consideration of seismic effects. Rock Mechanics and Rock Engineering, 52(11): 4287-4300.

[13] Gao Y H, Wu S C, Wang H, et al. (2016) Numerical simulation of joint direct shear test based on continuously yielding joint model. Journal of Central South University (Science and Technology), 47(4): 1253-1261.

[14] The Professional Standards Compilation Group of People’s Republic of China. GB/T 50218–2014 Standard for engineering classification of rock mass. Beijing: China Planning Press, 2014.

[15] Belem T, Homand F, Souley M. (2000) Quantitative parameters for rock joint surface roughness. Rock Mechanics and Rock Engineering, 33(4): 217-242.

[16] Mei X C, Cui Z, Sheng Q, et al. (2019) Analysis of the seismic response for an underground engineering in consideration of rock-concrete interaction. Chinese Journal of Rock Mechanics and Engineering, 38(Supp.2): 3634-3645.