Effect of normal stress on dynamic friction weakening of granitic rock joints under cyclic shear

Kai Zhang
State Key Laboratory of Hydroscience and Engineering, Tsinghua University, Beijing, China

Ling Zhu
Hydropower Engineering Technology Research Center, Academy of Science and Technology, China Three Gorges Corporation, Beijing, China

Li Cheng
China Renewable Energy Engineering Institute, Beijing, China

Qingchao Lyu
Powerchina Northwest Engineering Corporation Limited, Xi'an, China

Yaoru Liu
State Key Laboratory of Hydroscience and Engineering, Tsinghua University, Beijing, China

ABSTRACT: The friction strength evolution of rock joints subjected to cyclic dynamic loads is very vital to the safety and stability assessment of rock engineering during earthquakes and rock bursts. In this paper, cyclic shear experiments under different normal stress were carried out for granite joints based on a shaking table apparatus. The frictional behavior under cyclic shear, especially the dynamic evolution of friction strength, was investigated and the effect of normal stress on friction strength weakening was quantified. Based on experimental results, a hysteresis model is used to characterize the dynamic friction behavior of planar joints under cyclic shear. This model relates the evolution of friction strength to the number of cycles of cyclic shear. As the normal stress increases, the strength weakening ratio increases correspondingly, while the critical number of cycles (at which the residual strength is reached) remains essentially unchanged.

Keywords: Rock joints, Dynamic friction, Cyclic shear, Normal stress.

1 INTRODUCTION

The safety of many rock engineering projects is strongly affected by complex geological formations, especially joints and faults. Due to the excitation of seismic waves, the rock joints bear dynamic loads in addition to static loads, which will lead to cyclic fatigue damages (e.g. Liu et al. 2018 and He et al. 2021). Hence, it is crucial to develop a fundamental understanding of the strength evolution behavior of rock discontinuities under dynamic cyclic loading, which can be simulated as cyclic shear along the rock joint (Niktabar et al. 2017).

Many researchers have studied the frictional strength under dynamic cyclic loading conditions. The effect of frequency on the shear strength under dynamic cyclic loading was analysed by Ahola et al. (1996) and Ferrero et al. (2010). They found that the shear strength decreases as the number of cycles increases. Dang et al. (2020) conducted dynamic cyclic experiments on planar joints and revealed that the coefficient of friction changed cyclically with a change in the shear direction. Zhang et al. (2023) experimentally investigated the effect of cyclic shear loading on the frictional properties of a typical granite specimens and proposed a phenomenological model to describe the influence of loading frequency on the frictional strength weakening.

These previous studies provided important insights into the dynamic friction behavior of rock discontinuities under cyclic loads. However, it is worth noting that the observations and conclusions so far were mostly focused on the influence of loading frequency. The effect of the normal stress was not investigated and how this parameter would influence the friction behavior and frictional strength was still not clear.

Our research aims to advance the current knowledge about the frictional strength evolution of rock joints under dynamic cyclic loading, especially the effect of the normal stress. A series of cyclic friction tests is performed on planar granite joints under different normal stress, so that the friction behavior and the evolution of frictional strength under dynamic cyclic loading are investigated.

2 EXPERIMENT SETUP AND METHOD

2.1 The Experimental Apparatus

Cyclic shear experiments were conducted on a self-designed cyclic shear apparatus based on a shaking table (Zhang et al. 2023). As shown in Figure 1, the upper host rock is fixed and the lower slider rock is driven by a shear actuator with a sufficiently high stiffness (> 1 GN/m). The shear load is measured by a shear load cell with a resolution of 0.01 kN. A jack is used to apply normal forces through the reaction frame with a pressure sensor attached to the jack to monitor the normal stress level. The cyclic displacement is measured by a displacement sensor with a resolution of 0.001 mm. The data acquisition device can continuously record the shear force and shear displacement at a sampling frequency of 1000 Hz.

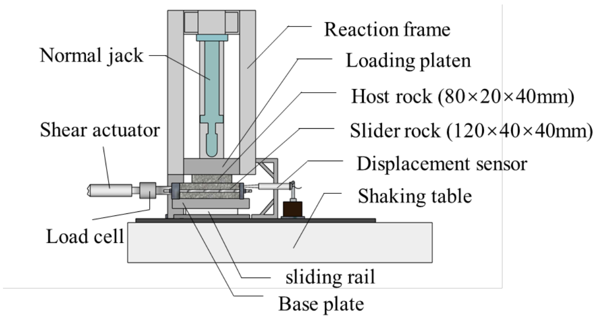


Figure 1. The cyclic shear loading test apparatus.

2.2 Sample Preparation

Saw-cut granite samples were prepared for the dynamic cyclic friction experiments. The planar joint separated each block into two parts: the upper fixed block is 80 mm × 20 mm × 40 mm, and the lower sliding block is 120 mm × 40 mm × 40 mm, such that their nominal contact area is 1600 mm^2. The intact granite samples show a uniaxial compressive strength of 83.58 MPa, a uniaxial tensile strength of 7.49 MPa, a density of 2.75 g/cm^3, and a Young's modulus of 12.55 GPa.

2.3 Experimental Procedure

The upper block was fixed and the lower mobile block was sheared repeatedly with the shear displacement governed by a sinusoidal function as:

$$u = A \cdot \sin 2\pi f t \tag{1}$$

where A is the displacement amplitude and f is the loading frequency. In this study, cyclic shear experiments were conducted at a loading frequency of 3 Hz, a displacement amplitude of 2 mm and under various normal stress of 1 MPa, 2.5 MPa, and 5 MPa. The experiment was stopped when it was clearly observed that the friction strength tended to stabilize. The temperature and humidity were at laboratory room conditions with little fluctuation (i.e., around 18°C temperature and 45% humidity). As shown in Figure 2, a typical loading cycle can be divided into four stages: forward advance (stage I) when the lower mobile block moves from the center to +2 mm, associated with a positive friction coefficient; forward return (stage II) when the lower block returns from +2 mm to the center , associated with a negative friction coefficient; backward advance (stage III) when the lower block moves from the center to -2 mm, associated with a negative friction coefficient; backward return (stage IV) when the specimen returns from -2 mm to the center , associated with a positive friction coefficient.

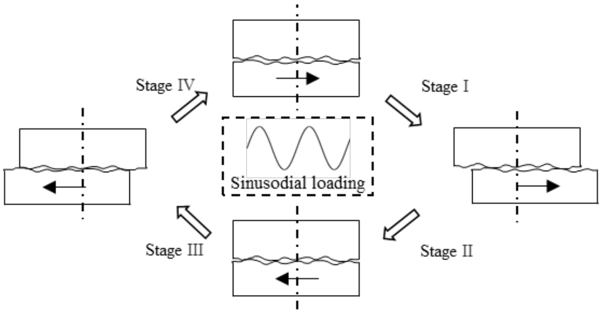


Figure 2. Schematic of the dynamic cyclic loading test procedures.

2.4 Calculation of Friction Coefficient

The coefficient of friction μ is calculated as the ratio of the driving shear force F_s to the normal force F_n, with F_n equal to the normal stress σ_n multiplied by the nominal contact area S of rock samples. In order to eliminate the impact of dynamic loading on the measured driving force, we adopt an approach taking into account the inertial force $F_{inertia}$ as:

$$\mu = \frac{F_{\mathrm{s}} - F_{\mathrm{inertia}}}{F_{\mathrm{n}}} \tag{2}$$

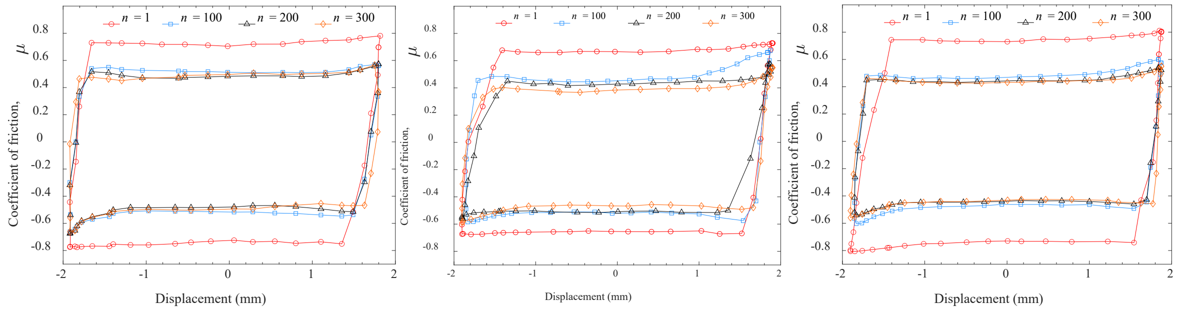
where $F_{inertia}$ is equal to the global mass m (the shear box and the specimen) driven by the shear load cell multiplied by the acceleration a derived as the second time derivatives of the displacement u.

3 RESULTS AND ANALYSIS

3.1 Dynamic Friction Behavior of Rock Joints under Cyclic Loads

Typical friction coefficient-displacement curves under different normal stress are shown in Figure 3. The curves exhibit typical hysteresis behavior, and continuously converges inward as the number of cycles n increases. Furthermore, the hysteresis loop shows a concave pattern, especially after a large number of cycles, suggesting that the frictional strength is not a constant during each loop.

The frictional behavior of the tested planar joints under different normal stress seems to be in general described by a dynamic friction characteristic model as shown in Figure 4. The friction coefficient-displacement curves under cyclic loading show typical hysteresis loops, with two concave curves on the top and bottom. OA, AB, BC, CO′ are the pre-peak, softening, hardening, and unloading stages, respectively. The lower half of the hysteresis loop is anti-symmetric with respect to the upper half. Three characteristic parameters are then proposed to represent the features of the friction coefficient in a loop: (i) the friction coefficient at point A denoted as μ_{peak}; (ii) the friction coefficient at point B denoted as $\mu_{softening}$, which represents the friction coefficient with the highest softening degree; (iii) the friction coefficient at point C denoted as $\mu_{hardening}$, which corresponds to the high friction coefficient at the end of the hardening stage. They are subjected to a relationship of $\mu_{\text{hardening}} > \mu_{\text{peak}} > \mu_{\text{softening}}$.



(a) 1 MPa (b) 2.5 MPa (c) 5 MPa

Figure 3. Hysteresis loops of the friction coefficient versus shear displacement for rock joints under cyclic loadings of different normal stress.

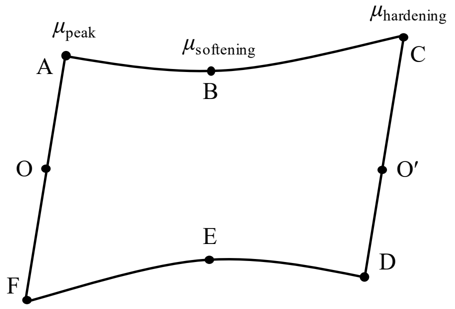


Figure 4. The dynamic friction characteristic model.

3.2 *Evolution of the Coefficient of Dynamic Friction*

A typical evolution curve of friction coefficient μ_{peak} with the number of cycles is shown in Figure 5. As the number of cycles increases, the friction coefficient decreases from the initial peak value ($\mu_{\text{i}} = 0.71$) to a steady-state value ($\mu_{\text{ss}} = 0.41$), exhibiting a clear frictional weakening behavior. An exponential function is used to fit the evolution of the friction coefficient with the number of cycles as:

$$\mu(n) = \mu_{\text{ss}} + (\mu_{\text{i}} - \mu_{\text{ss}})\exp\left(\frac{n-1}{n_{\text{c}}-1}\ln\alpha\right) \tag{3}$$

where μ is the coefficient of friction for the nth cycle, μ_{ss} is the steady-state coefficient of friction, μ_{i} is the initial coefficient of friction, and n_{c} is the critical number of cycles at which the frictional strength decreases to a stable value. Here, following the suggestions by Mizoguchi et al. (2007), the constant α is defined to be 5%, which means that μ–μ_{ss} reduces to 5% of the total friction drop μ_{i}–μ_{ss} when the critical number of cycles n_{c} is reached. To quantify the frictional weakening, we also define the weakening ratio μ_{loss} of dynamic frictional strength as:

$$\mu_{\text{loss}} = \frac{\mu_{\text{i}} - \mu_{\text{ss}}}{\mu_{\text{i}}} \tag{4}$$

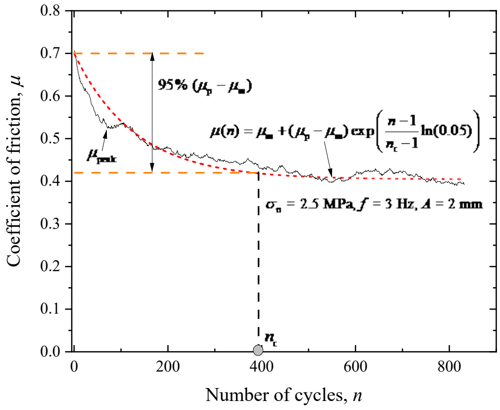
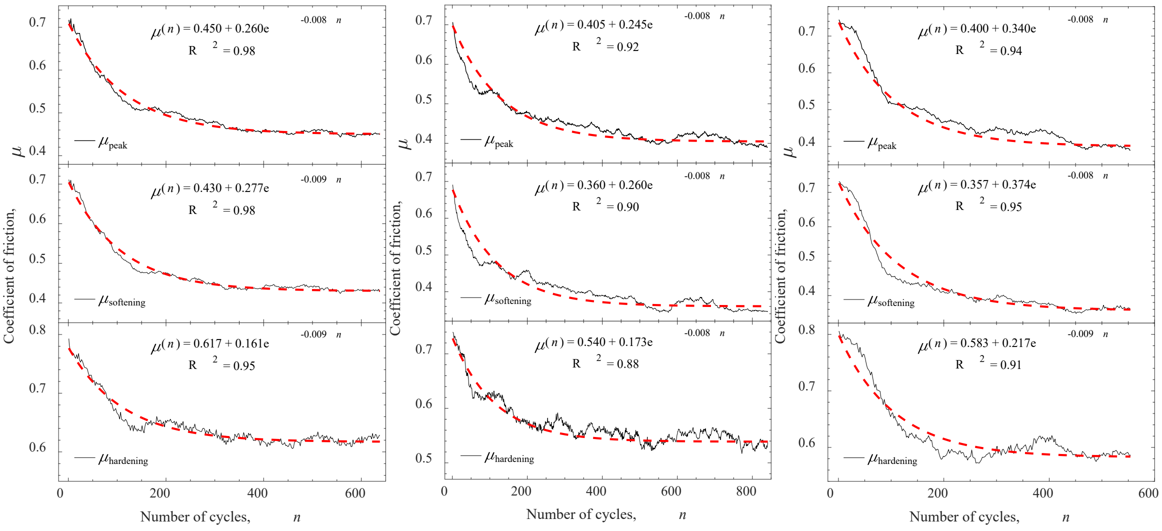


Figure 5. A typical evolution curve of the friction coefficient of rock joints under cyclic loads.

3.3 *Effects of Normal Stress on Cyclic Friction*

Variations of the friction coefficients (μ_{peak}, $\mu_{\text{softening}}$, and $\mu_{\text{hardening}}$) with the number of cycles under different normal stress are shown in Figure 6. The friction parameters μ_{peak}, $\mu_{\text{softening}}$, and $\mu_{\text{hardening}}$ decrease synchronously with the increasing number of cycles. The exponential law, i.e., Equation 3, can in general well capture the evolution of these three friction parameters with n. For all experiments of different normal stress performed, planar granitic joints exhibited a pronounced drop of the friction coefficient from the peak to the steady-state value.



(a) 1 MPa (b) 2.5 MPa (c) 5 MPa

Figure 6. Frictional strength evolution as a function of the number of cycles for μ_{peak}, $\mu_{\text{softening}}$, and $\mu_{\text{hardening}}$ under different normal stress.

In order to qualify the influence of normal stress on cyclic friction, We compare the critical number of cycles n_c and weakening ratio μ_{loss} under different normal stress. As shown in Table 1, the critical number of cycles n_c shows no big difference with the varying normal stress, which indicates that the critical number of cycles n_c may be a parameter independent of normal stress. As the normal stress increases, the weakening ratio μ_{loss} increases to different extent. This indicates that higher normal stress can induce stronger wear of the rock surface during cyclic shear, thus leads to a lower residual friction coefficient. However, this difference in the weakening ratio is not achieved by increasing the number of cycles. It can be assumed that although a higher normal stress may result in a greater weakening radio in the rock surface, the weakening degree accumulated in each cycle also increases with the increased normal stress.

Table 1. Summary of critical number of cycles and weakening radio under different normal stress.

Conditions	μ_{peak}		$\mu_{softening}$		$\mu_{hardening}$	
	n_c	μ_{loss}	n_c	μ_{loss}	n_c	μ_{loss}
1 MPa	364	37.3%	344	39.1%	347	20.7%
2.5 MPa	398	42.2%	378	47.1%	360	26.0%
5 MPa	356	45.9%	361	51.1%	345	27.3%

4 CONCLUSION

In this study, a series of cyclic friction tests was conducted on planar granite joints under different normal stress. The friction behavior especially the dynamic evolution of the frictional strength under cyclic loading was investigated, with the influence of normal stress on the frictional strength weakening analyzed. Based on the experimental results, a hysteresis model is successfully used to characterize the dynamic friction behavior of planar joints under cyclic shear under different normal stress. The study also found that cyclic motions of rock joints will cause significant weakening in frictional strength with the number of cycles, and this weakening behavior is highly related to normal stress, which should be taken into consideration in current codes of practice and numerical simulation.

ACKNOWLEDGEMENTS

This work was supported by the National Natural Science Foundation of China (Grant No. 41961134032) and the Swiss National Science Foundation (Grant No. 189882).

REFERENCES

Ahola, MP., Hsiung, SM. & Kana DD. 1996. Experimental study on dynamic behavior of rock joints. *Developments in geotechnical engineering* 79 (79), pp. 467-494. DOI: 10.1016/S0165-1250(96)80037-X

Dang, WG., Konietzky, H., Fruehwirt, T. & Herbst, M. 2020. Cyclic frictional responses of planar joints under cyclic normal load conditions: Laboratory tests and numerical simulations. *Rock Mechanics and Rock Engineering* 53 (1), pp. 337-364. DOI: 10.1007/s00603-019-01910-9

Ferrero, AM., Migliazza, M. & Tebaldi, G. 2010. Development of a new experimental apparatus for the study of the mechanical behavior of a rock discontinuity under monotonic and cyclic loads. *Rock Mechanics and Rock Engineering* 43 (6), pp. 685-695. DOI: 10.1007/s00603-010-0111-8

He, MM., Zhang, ZQ. & Li, N. 2021. Experimental investigation and empirical model to determine the damping and shear stiffness properties of soft rock under multistage cyclic loading. *Soil Dynamics and Earthquake Engineering* 147, pp. 106818. DOI: 10.1016/j.soildyn.2021.106818

Liu, Y., Dai, F., Feng, P. & Xu, NW. 2018. Mechanical behavior of intermittent jointed rocks under random cyclic compression with different loading parameters. *Soil Dynamics and Earthquake Engineering* 113, pp. 12-24. DOI: 10.1016/j.soildyn.2018.05.030

Mizoguchi, K., Hirose, T., Shimamoto, T. & Fukuyama, E. 2007. Reconstruction of seismic faulting by high-velocity friction experiments: An example of the 1995 kobe earthquake. *Geophysical Research Letters* 34, pp. L01308. DOI: 10.1029/2006GL027931

Niktabar, SMM., Rao, KS. & Shrivastava, AK. 2017. Effect of rock joint roughness on its cyclic shear behavior. *Journal of Rock Mechanics and Geotechnical Engineering* 9 (6), pp. 1071-1084. DOI: 10.1016/j.jrmge.2017.09.001

Zhang, K., Liu, YR., Lei, QH., Hou SK. & Yang, Q. 2023. Effect of Dynamic Cyclic Shear on Frictional Strength Weakening of a Plane Joint. *Soil Dynamics and Earthquake Engineering* 165, pp. 107670. DOI: 10.1016/j.soildyn.2022.107670