Study on the mechanism of dynamic slip-weakening for a rock material interface based on a vibration experiment

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Abstract. Slip-friction of faults and joint fractures is of great significance in the study of rock mass structural engineering stability and earthquake generation mechanism. Laboratory friction experiment is a great method to determine the frictional strength of rock interfaces. A large number of low-velocity experiments has been conducted to explain the friction mechanism in the regime of direct shear mode. However, the friction mechanism in the regime of vibration mode has rarely been studied. To study the slip-friction mechanism of rock interface under the vibration mode, a dynamic friction experiment with two blocks on a vibrating platform was performed. The experiments were conducted with hard granite samples at a vibration frequency of 1–10Hz, vibration amplitude 0.5–5mm, and normal stress of 0.5–4.5MPa. The results demonstrate that slip- and frequency-weakening phenomena were noticed and the general quantitative relationship of the three characteristic friction parameters is $\mu_3 > \mu_1 > \mu_2$. Moreover, the normal stress has a significant effect on the weakening degree of the friction coefficient, and the change in the surface roughness may correlate with the change in the weakening degree.

1. Introduction

The main dominant factor of rock mass discontinuity, heterogeneity, and anisotropy is the structural plane. Under cyclic and dynamic loads caused by earthquakes or blasting, the changes in deformation and strength caused by the closure or slip of structural surfaces may play a significant role in the instability and destruction of ground or underground structures [1]. Therefore, the study of the friction properties of rock mass structural planes under cyclic frictional loading can provide a reliable basis for rock mass structural engineering stability analysis and reinforcement design. Many studies have investigated the shear strength of rock joints, the relationship between joint roughness and strength, the effect of dilatancy, the seepage law during shearing and numerical simulation of shear properties, and the characteristics of three-dimensional (3-D) jointed rock mass morphology [2-6]. Based on the cyclic shear tests of artificial sawtooth joints, Plesha [7] reported that the peak strength decreased as the cyclic shear loading increased. Jafari et al. [8] analyzed the influence of cyclic shear loading and normal stress on the mechanical properties of joints. They found that the joint shear strength decreased as the number of cycles increased. The change in strength under low normal stress is dominated by the surface sliding wear, while the change in strength under high normal stress is dominated by the shearing effect of surface sawtooth. Lee et al. [9] conducted cyclic shear tests on granite and marble samples. The surface morphology characteristics of the joints were obtained with a surface laser scanner before and after shearing, and the changes in the defined surface...
parameters during cyclic shearing were analyzed. Thus, they concluded that the wear of the convex body on the joint surface was due to plastic deformation. These experiments were all conducted with the reciprocating low-velocity direct shear experiment. However, the movement of the structural plane under real in-situ cyclic loading should be treated as a variable speed process, which means it may accelerate from the origin position and then decelerate to the other side after attaining maximum speed. Moreover, the majority of the related research focuses on the low-velocity regime, whose deformation and strength effects do not match the real situation. Conversely, low- and high-velocity friction experiments have been discussed extensively in the literature [10-15]. However, an intermediate velocity regime is required between the low- and high-velocity regime to better understand the transition process of landslide failure and growth of precursory slip to a large earthquake, especially for cyclic friction experiments. In this study, a simple harmonic motion is adopted to simulate the displacement caused by a cyclic load, and a cyclic friction experiment of granite samples is conducted under varying frequencies and normal stresses. Three characteristic friction parameters and the evaluation model of the weakening degree were extracted from the friction curve. In addition, the relationship between the three characteristic friction parameters and the frequency or normal stress was analyzed, and the evolution of surface roughness is studied as well.

2. Experiment equipment and samples

2.1. Experimental setup

Figure 1 shows the shaking table equipment (State Key Laboratory of Hydraulic Structures of Tsinghua University) used in this study. Two shaking tables, which are actuated by hydraulic loading, are placed horizontally. Both tables vibrate in the single axial direction and have a dimension of 1.5 × 1.5 m, with a frequency of 0–50 Hz and a maximum load of 2000 kg. The rock specimen is fixed on one table using a fixing device, while the other table acts as a shear actuator to drive the rock specimen to vibrate cyclically. The normal stress is applied through an adjustable jack, which is up to 40 MPa. The experiments were conducted with a vibration frequency of 1–10 Hz, vibration amplitude 0.5–5 mm, and normal stress of 0.5–4.5 MPa.

2.2. Material properties and surface preparations

To simulate the friction behavior of the shallow surface under seismic loading, granite samples were uniformly used as the interface friction material. The friction surface is a saw-cut surface with an area of 10 × 10 cm. The density, compressive strength, and Poisson’s ration of granite were taken as 2.79 g/cm³, 1.5 kg/cm², and 0.3, respectively.

2.3. Instrumentation
The main physical quantities measured in this experiment were the frictional force, displacement, roughness, and acoustic emission signals. The force and displacement were measured with a high-frequency dynamometer with a sampling frequency of 1000 Hz. A 3-D scanner was used to observe the surface of the granite before and after the experiment, which is used to reflect changes in surface abrasion by creating a 3-D point cloud on the surface of the object. The AE testing and analysis system produced by the American-based Acoustic Physics Company was used to detect the acoustic emission characteristics of rocks under varying vibration frequencies. During the experiment, the signal amplifier threshold value, probe resonance frequency, and the sampling frequency were set to 40 dB, 60 dB, 20–400 kHz, and 1M times/S respectively.

3. Experimental procedure and group

First, the upper and lower fractured rock samples were installed into the shear box to ensure complete contact and also to ensure that the loading axis of the shear jack coincides with the centerline of the sample. Then, normal stress is applied until the measured value is constant for some time. This is done to ensure that the loading force remains unchanged during the experiment. After setting up the measuring and data collecting instruments, the shaking tables are arranged, and the cyclic friction experiment under vibrating loads is started.

The cyclic friction process of the fractured rock sample is shown in Figure 2. Processes ① to ④ represent the whole cyclic friction process. At the onset, the upper and lower parts of the sample are in an anastomosed state. Subsequently, the upper sample slips to the right with a displacement of $\delta_{\text{max}}$ (process ①). Afterward, the slipping direction is changed and the upper sample moves to the left with a displacement of $-\delta_{\text{max}}$ (process ②) to attain a resultant displacement of 0 mm before further moving to the extreme left (process ③) with another displacement of $-\delta_{\text{max}}$. The slipping direction is changed again and the upper sample moves to the right (process ④) with a displacement of $\delta_{\text{max}}$ to attain a resultant displacement of 0 mm and then the processes are repeated all over again.

![Fig. 2. Schematic representation of the cyclic friction process](image)

| Run#  | Frequency (Hz) | Amplitude (mm) | $\sigma_N$ (MPa) |
|-------|----------------|----------------|-----------------|
| 125   | 1              | 2              | 2.5             |
| 325   | 3              | 2              | 2.5             |
| 310   | 3              | 2              | 1               |
| 315   | 3              | 2              | 1.5             |
| 320   | 3              | 2              | 2               |
| 330   | 3              | 2              | 3               |
| 525   | 5              | 2              | 2.5             |
| 1025  | 10             | 2              | 2.5             |

4. Data processing
Due to the influence of the environmental conditions on the experiment, the waveform was distorted and mixed into the noise in the process of wave propagation. In this study, the spectrum analysis of the waveforms of the frictional force was performed to obtain the features of the frictional force. Based on this, signal recognition and noise filtering were conducted.

As an example, consider run #325. Shown in Figure 3a are the waveforms of the signals of the frictional force at a frequency of 3 Hz and an amplitude of 2 mm. The corresponding frequency domains of the time-domain signals were obtained via the fast Fourier transform performed in MATLAB software.

As can be seen in Figure 3c, the frequency in the low-frequency region is 0 Hz, which corresponds to the DC component and thus should be filtered. Figure 3d shows the spectrum analysis of the raw data at 0–50 Hz. The signal is concentrated between 0–50 Hz, with a maximum amplitude of 3 Hz (Figure 3d), which is the input frequency of the shaking table. The other signals at 9 and 15 Hz that are less in amplitude follow suit. These relative high-frequency signals could be interpreted as the effect of the collision, squeezing, and shearing of asperities during the friction process of the rock sample, which can reflect the mechanical behavior of the friction. Therefore, the filter interval is finally determined to be 2.5–50 Hz.

Fig. 3. Data of the first 20 seconds for run f2p1. (a) Raw data, (b) filtered data, (c) spectrum analysis of raw data in the low-frequency region, and (d) Spectrum analysis of raw data in the frequency region of 0–50 Hz.

5. Results and analysis

5.1 Relationship between the characteristic friction parameters and varying frequencies
Fig. 4. (a) Extraction of key friction parameters in 10 seconds. (b) Variation of the coefficient of friction with time for the first second. (c) $\mu_1, \mu_2, \mu_3$ on average at a frequency range of 1–10 Hz

Each half of the vibration period was taken as a unit, and a MATLAB-based algorithm was used to extract the friction characteristic parameters within every single unit (Figure 4a), including $\mu_1 (\circ)$, $\mu_2 (*)$, and $\mu_3 (\star)$. As shown in Figure 4b, $\mu_1$ is the yield friction coefficient, which represents the first peak of the friction coefficient in each unit; $\mu_2$ is the weakening friction coefficient, which represents the lowest friction coefficient during the friction process; and $\mu_3$ is the peak friction coefficient, which represents the maximum friction coefficient during the friction process.

Due to the cyclicity and anti-symmetry of the friction coefficient curve, the positive and negative values, respectively, indicate the friction coefficients of the two opposite directions of movement, with little difference. For convenience, the characteristic parameters of the two units in a cycle are averaged in the later analysis.

As shown in Figure 4b, a dramatic slip-weakening behavior was observed in every interval unit, and the general quantitative relationship among the three characteristic friction parameters is given as $\mu_3 > \mu_1 > \mu_2$. Moreover, the frequency-weakening phenomenon was noticed in all three characteristic friction parameters. As shown in Figure 4c, the changing curve of the three characteristic friction parameters on average with different frequencies is given out. From observation, it is clear that the characteristic friction coefficient weakens as the frequency increases and this trend slows down from 3 Hz; this indicates that the wearing of the contact surface and frequency are closely related. When the frequency is smaller than 3 Hz, the wear tends to become stable. It is expected that because of the low speed of cyclic friction, the wear rate of the contact surface should be slower, and thus the greater the resistance barrier.

5.2 Relationship between the characteristic friction parameters and varying normal stress
The shear displacement and coefficient of friction are combined with the hysteresis curve through time alignment (Figure 5). The three characteristic friction parameters mentioned in Figure 4b are marked with red short lines on the hysteresis curve. The relationship between the hysteresis curve and cyclic friction motion is also explained.
Figure 5 shows the hysteresis curve of the friction coefficient and slipping displacement (run #330). For convenience, when the slipping displacement and the initial slipping displacement direction are the same (relative to the zero position), it is regarded as a positive direction, otherwise negative. The friction starts from point O and proceeds along the direction of A→B→C→D. The curves in quadrants 1 to 4 correspond to the experimental curves in the friction stages ① to ④ in Figure 3.

Based on geometry, the friction hysteresis curve is an antisymmetric figure, so only half of the curve is needed. Thus, the half part of the positive friction coefficient is selected for analysis. For every one cycle, when the friction direction slips from negative to positive displacement, the friction coefficient first reaches the yield friction coefficient \( \mu_1 \), and then accelerates to the weakening friction coefficient \( \mu_2 \). The friction coefficient then increases with increasing slipping displacement, and finally, it reaches the peak friction coefficient \( \mu_3 \). In the initial stage of the cyclic friction, the distance between adjacent hysteresis loops is quite different. However, as the cycle increases, the hysteresis loops tend to coincide, and the characteristic friction coefficient changes slightly, which indicates a worn-out interface. Furthermore, the hysteresis loop is thicker in the middle and thinner on both sides, which means the weakening friction coefficient \( \mu_2 \) changes more rapidly than \( \mu_1 \) and \( \mu_3 \).

Figure 6 shows the weakening degree of the three friction characteristic coefficients in the last cycle \( (\mu^{last}) \) relative to that of the first cycle \( (\mu^{1st}) \) under varying pressures. The weakening degree is defined by:

\[
\text{weakening degree} = \frac{\mu^{1st} - \mu^{last}}{\mu^{1st}}
\]
As shown in Figure 6, the three characteristic friction parameters have different weakening degrees. From a clear observation, an empirical law could be established which states that except for a normal stress level of 2.5 MPa, the weakening degree increases as the normal stress increases. The weakening degree is the highest when the normal stress reaches 3 MPa, and the weakening degree of $\mu_2$ reaches 50%, which corresponds to the hysteresis curve in Figure 5. Hence, it can be concluded that the normal stress has a significant effect on the weakening degree of the friction coefficient.

5.3 The relationship between macro-strength and micro-morphology
This section primarily studies the evolution of roughness and friction coefficient under varying normal stresses. For the sake of processing and comparison, the upper surface of the granite sample is uniformly scanned before and after the experiment with the aid of a 3-D scanner, which is used to reflect changes in surface abrasion by creating a 3-D point cloud on the surface of the object [16]. To observe the roughness of the surface before and after friction, the surface morphology of the rock sample was converted before and after vibration to the same coordinate system through the linear transformation of coordinates. Subsequently, the optimal alignment algorithm in Geomagic Qualify (3D system) was used to obtain the surface morphology of the sample before and after friction and also to calculate the change in surface roughness height. To avoid the edge effect, the central area of 90 × 90 mm was extracted for analysis and comparison during scanning. The accuracy of the calculated result reached 5 μm. The change in roughness is characterized by the wear volume calculated from the surface morphology before and after the experiment (Table 2 and Figure 7).

| Table 2. Wear volume for varying normal stresses                     |
|---------------------------------------------------------------|
| Normal stress (MPa)       | 1     | 1.5   | 2     | 2.5   | 3     |
| Wear volume (mm)          | 60.5426 | 112.235 | 143.8203 | 55.2356 | 190.0485 |

Figure 8 compares the wear volume and weakening degree. It turns out that the change in roughness corresponds to the change in the weakening degree. It indicates that the essential reason for the
decrease in friction parameters is the change of the wear volume of the contact surface, which causes more interface uniformity so that less resistance is needed to overcome the slip.

![Graph]

**Fig. 8.** Comparison of wear volume and weakening degree under 1–3 Mpa

6. Conclusions
In this study, three characteristic friction parameters and a quantitative method of determining the friction weakening degree have been defined based on a cyclic friction experiment at varying vibration frequencies and normal stresses. The strength evolution of the structural surface under cyclic load, as well as its correlation with the frequency of vibration and normal stress, was studied. The key conclusions drawn from this research work are as follows.

1. Slip- and frequency-weakening effects were noticed, and the general quantitative relationship of the three characteristic friction parameters was \( \mu_3 > \mu_1 > \mu_2 \). In the early several cycles of hysteresis curves, the distance between adjacent hysteresis loops was found to be quite dispersed, but as the cycle increased, the hysteresis loops coincided.

2. Normal stress had a significant effect on the weakening degree of the friction coefficient. The greater the normal stress, the higher the weakening degree.

3. The change in the surface roughness seemed to correlate with the change in the weakening degree, which revealed that the change in the wear volume of the contact surface was the essential reason for the decrease in the characteristic friction parameters.

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