Experimental study on post-peak stick-slip failure of three different rock joints under direct shear tests

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Abstract. For discovering the post-peak stick-slip failure characteristics of joint in rock mass and mechanism of the post-peak shear failure, a coupling 3D scanning and 3D engraving method are presented to create three kinds of rock joints (sandstone, marble, and granite) with identical morphology, and corresponding direct shear tests and synchronous Acoustic emission monitoring are conducted. A multi-aspect analysis is performed to recognize the mechanical behavior of post-peak stick-slip and its meso-fracture mechanism of rock joint. The results indicate that the occurrence of post-peak stick-slip failure of rock joint mainly depends on rock types, and its failure type changes with the increase in the normal stress. The post-peak stick-slip phase has the same failure type and dominant frequency range as those of the shear load peak phase. Thus, the post-peak stick-slip failure can be understood as a small shear peak failure. The failure type of the shear load peak can be used to predict post-peak stick-slip failure of rock joint. It has important reference significance for precursor identification of shear disaster in engineering rock mass.

1. Introduction
Due to the composite structure of rock mass as "intact rock + rock joint"[1, 2], the deformation of the rock surrounding an excavation occurs primarily along natural joint, bedding planes, or discontinuities[3]. The shear deformation and failure modes of the rock joint are often the key factors
for the instability of the engineering rock mass[4-6], therefore, understanding the full-stage shear deformation and failure modes of rock joint is the basis of engineering stability. Many scholars have conducted shear tests at different shear rates, loading conditions, and temperatures, and substantial research progress has been made[7-10]. However, the upper and lower blocks of the joint specimen are closely fitted together in the shearing process, thus hindering the understanding of the damage evolution of shearing process. Therefore, the research results of many scholars mainly focus on the overall performance of joint shear tests, such as shear strength and deformation[11]. Due to incompetent damage studies of the shearing process, mechanical behavior and failure mechanism of the post-peak stick-slip failure, an important factor in the shear failure mechanism manifesting as the continuous relaxation of the shear stress and sharp jump of the shear displacement, have received less attention.

Acoustic emission (AE), as a phenomenon of instantaneous elastic waves produced by the rapid release of strain energy due to mesoscopic damage or fracture in the material, is an excellent method for non-damage and real-time monitoring[12, 13]. As the information released by material damage, AE contains a wealth of information on the fracture source. Through reverse analysis of the AE signal, the type and degree of the fracture can be determined. Many scholars have used AE to study the mechanism of failure[14, 15]. Moradian, Ballivy[16] conducted shear test and AE monitoring of joint, and showed the sufficient accuracy of AE to monitor shear failure processes.

To study the characteristics of the post-peak stick-slip failure of joint in rock mass and better understand the mechanism of the post-peak shear failure, we used 3D scanning and 3D engraving to create three kinds of rock joints (sandstone, marble, and granite) with identical morphology, and performed direct shear tests and synchronous AE monitoring. A multi-aspect analysis was done to recognize the mechanical behavior of post-peak stick-slip and its meso-fracture mechanism of rock joint.

2. Shearing experimental scheme

We obtained a batch of joint specimens with the same morphology by 3D scanning and 3D engraving techniques (the specific implementation process can be obtained from reference[6]), including 9 sandstone joint specimens, 9 granite joint specimens, and 9 marble joint specimens, the joint specimen is 150 mm × 120 mm × 150 mm in size, and the overall joint roughness coefficient value is about 12–14 (Figure 1). We performed uniaxial compression tests on cylindrical specimens of three kinds of rocks to obtain their uniaxial compressive strengths. The uniaxial compressive strengths of sandstone, marble, and granite were 44.63 MPa, 77.61 MPa, and 204.61 MPa, respectively. According to the results of uniaxial compressive test and pre shear test, we applied low, medium, and high normal stresses on joint specimens to make the shear damage characteristics different (Table 1); three repeated shear tests were conducted for each rock under normal stress, and a total of 27 shear tests were done for the three types of rocks.

| Rock type    | Low normal stress | Middle normal stress | High normal stress |
|--------------|-------------------|----------------------|-------------------|
| Sandstone    | 0.15 MPa          | 0.5 MPa              | 2 MPa             |
| Marble       | 0.3 MPa           | 1 MPa                | 4 MPa             |
This direct shear test was conducted under constant normal stress by a servo-control testing machine (Figure 2). In this test, a displacement control loading mode was adopted with a loading ratio of 0.005 mm/s and a maximum displacement limitation of 12 mm to ensure complete shear damage of natural rock joint specimen and obtain the corresponding shear load curve. The surface of granite and marble’s joint specimen were sprinkled with red ink, while that of the sandstone joint specimen was sprinkled with black ink, considering themselves texture color. Thus, the damaged area on the surface of the joint can be shown in different color surface after the shear test.

The AE monitoring system used 16-channel monitoring equipment produced by the PAC. Due to the shear damage near the joint’s surface, the AE positioning method used plane positioning. For better collection of AE signals, a total of 6 AE sensors were distributed on both sides of the lower block along the shear direction, 3 AE sensors are distributed on each side, 6 sensors are in the same horizontal plane and staggered distribution in the plane (Figure 2). The value of the AE amplifier was set as 40 db, the threshold of the AE monitoring system was set to 40 db and the sampling rate was set to 1 MSPS.

| Granite   | 2 MPa | 4 MPa | 10 MPa |
|-----------|-------|-------|--------|

**Figure 1** Joint specimens of the three types of rock
3. Test results

According to the experimental scheme, the direct shear tests and AE monitoring were carried out for joint specimens, the shear damage characteristics (Figure 3) and shear load curves (Figure 4 a b c) were obtained for the three rock joints. Based on the shear damage characteristics, it was observed that with the increase of the normal stress, the shear damage of the joint is more serious, and the damage areas are concentrated in several areas. According to the shear load curves of three rock joints, it was observed that the sandstone joint had no stick-slip failure at the post-peak stage under low, medium, and high normal stress, while the marble and granite joints always had stick-slip failure at the post-peak stage under low, medium, and high normal stress, indicating that the occurrence of stick-slip failure in rock joint mainly depends on the rock types.

To study the degree of stick-slip failure, the oscillation ratio of granite and marble joints were calculated (The oscillation ratio is the maximum post-peak shear load oscillation divided by the peak shear load). It found that the oscillation ratio increases with the increase in normal stress, basically showing a linear growth (Figure 4 d). The oscillation ratio of granite joint is about 10%, 18%, and 29% under low, medium, and high normal stress. The oscillation ratio of marble joint is about 0.6%, 1%, and 1.7% under low, medium, and high normal stresses. The post-peak stick-slip failure of granite joint is much larger than that of marble joint.
Figure 3 Shear damage characteristics of three rock joints

Figure 4 Test curves (a) shear load curve of sandstone joint (b) shear load curve of marble joint (c) shear load curve of granite joint (d) stick-slip ratio curve of joint

4. Analysis of post-peak stick-slip failure mechanism

AE signal is the elastic wave released when the material is damaged, containing abundant information of fracture source. By analyzing AE signal, the type and degree of fracture can be determined. Based on this, we analyzed the AE signal in the shear process of joint to determine the failure type and degree of post-peak stick-slip failure and reveal the post-peak stick-slip failure mechanism of the joint.
We used AE parameter analysis method, more specifically RA vs. AF method, to distinguish the type of fracture. RA vs. AF is a common AE method in which the type of fracture is distinguished by combining RA and AF values of AE signal (Eq. 1 and Eq. 2). Tensile fracture has higher AF value and lower RA value while shear fracture has lower AF value and higher RA value (Figure 5 a). This method has the advantages of fast processing speed and low requirement for the number of sensors [17, 18]. We used the dominant frequency of the AE signal to determine the degree of fracture. By transforming the frequency spectrum of the AE signal, the frequency when the amplitude reaches the maximum is the dominant frequency of the signal (Figure 5 b). The dominant frequency of the signal can reflect the damage degree of the fracture and is inversely proportional to the degree of fracture. The larger the dominant frequency, the smaller the degree of fracture. Many scholars use the dominant frequency to study the failure process [19, 20].

\[
RA = \frac{\text{Rise time}}{\text{the maximum amplitude}} \quad \text{(Eq. 1)}
\]

\[
AF = \frac{\text{Counts}}{\text{Duration}} \quad \text{(Eq. 2)}
\]

**Figure 5** AE analysis method (a) Classification type of fracture (b) AE signal spectrum conversion

Using the RA vs. AF method, the AE signals in the shear process of rock joint were identified and the type of fracture were determined. Taking 100s as a period, the entire shearing process is divided into 25 periods, the number of tensile and shear fractures in each period were counted. The shear load curve and the fracture type evolution process of rock joint under different normal stresses were obtained (Figure 6). It was found that the main failure type of rock joint in the shear process changes with the increase in normal stress, the overall failure is mainly shear failure under low normal stress, tensile-shear mixed failure under medium normal stress, and tensile failure under high normal stress. In the marble joint and granite joint where stick-slip failure occurs, the post-peak stick-slip failure type also changes with the increase in normal stress. The post-peak stick-slip failure is shear failure under low normal stress, shear tensile mixed failure under medium normal stress, and tensile failure under high normal stress. The post-peak stick-slip failure type is consistent with the overall failure type of joint.
We calculated the dominant frequency of each AE signal in the shear process of rock joint. Combined with the shear load curve, the dominant frequency evolution process of rock joint under different normal stresses can be obtained (Figure 7). It was found that the dominant frequency range is 60 kHz–320 kHz near the shear load peak. In the phase of post-peak stick-slip failure of marble and granite joints, the dominant frequency range is also 60 kHz–320 kHz, its dominant frequency range is consistent with the dominant frequency range near the shear load peak. However, there are fewer low-frequency signals in the post-peak stick-slip phase, indicating that the post-peak stick-slip phase has less damage than that near the shear load peak.

By comparing the failure type and failure degree of post-peak stick-slip phase and shear load peak phase, it was observed that post-peak stick-slip phase has the same failure type and the same dominant frequency range as shear load peak phase. The post-peak stick-slip failure can be understood as a small shear peak failure. Thus, the failure type of the shear load peak can be used to predict post-peak stick-slip failure of rock joint. This has important reference significance for precursor identification of shear disaster in engineering rock mass.

Figure 6 Fracture type evolution process of rock joint under different normal stresses
5. Conclusions

In this paper, direct shear tests and AE monitoring were performed for three kinds of rock joints. Combined with shear load curves and AE back analysis, the post-peak stick-slip failure is analyzed from multiple aspects. The following conclusions can be drawn from this study:

(1) The occurrence of post-peak stick-slip failure of rock joint mainly depends on rock types. Sandstone joint has no post-peak stick-slip failure even under higher normal stress, while marble and granite have obvious post-peak stick-slip failure even under lower normal stress. When post-peak stick-slip failure occurs, the amplitude of stick-slip oscillation increases with the increase in the normal stress.

(2) The failure mode of post-peak stick-slip changes with the increase in the normal stress. The post-peak stick-slip failure mode is shear failure under lower normal stress, tensile-shear mixed failure under middle normal stress, and tensile failure under high normal stress.

(3) The dominant frequency range of the AE signals in the post-peak stick-slip phase is about 60 kHz–320 kHz and its dominant frequency range is consistent with that near the shear load peak. However, there are fewer low-frequency signals in the post-peak stick-slip phase, implying that the post-peak stick-slip phase has less damage than that near the shear load peak phase.

(4) The post-peak stick-slip phase has the same failure type and the same dominant frequency range as the shear load peak phase. The post-peak stick-slip failure can be understood as a small shear peak failure. Thus, the failure type of the shear load peak can be used to predict post-peak stick-slip failure of rock joint.

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