Effects of normal stiffness on the shear behaviors and acoustic emissions of rock joints

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Abstract: In this study, direct shear tests were conducted on plaster joints under various boundary conditions. During shearing, the acoustic emission (AE) was measured by the PAC AE system. The damage of the asperities was evaluated based on the AE signals. The effects of the normal stiffness on the shear behavior and asperity damage were studied, and the corresponding AE characteristics were analyzed. The results show that the peak shear stress for rock joints under constant normal load boundary conditions is larger than that under the CNS boundary conditions. The shear dilation decreases as the normal stiffness increases. The AE signals are more active in the post-peak stage for the rock joints sheared under higher normal stiffness conditions. Both the AE count and AE energy rate increase with an increase in the normal stiffness. Thus, the total AE events increase with increasing normal stiffness.

1. Introduction
Understanding the shear behaviors of rock joints is of critical importance in many practical applications, such as slope engineering, tunnel excavation, and natural gas/oil production. Since the 1960s, the shear behavior of rock joints has been extensively investigated through laboratory testing, theoretical analysis, and numerical modeling [1-4]. Primarily, the investigations focused on the mechanical response of rock joints under constant normal load (CNL) conditions. The shear behavior of rock joints is influenced by various factors, including joints surface roughness, normal stress, rock type, shear direction, and scale effect [5-9]. Among such factors, joint surface roughness is considered as one of the most critical factors and has a significant impact on the shear strength of rock joints. Thirukumaran and Indraratna [10] reported that the shear behavior of rock joints involves the degradation of joint asperities. Moreover, in their study, they concluded that the shear strength is dominantly borne by the asperities. Thus, accurately evaluating the degradation of asperities during shearing is important. Acoustic emission (AE), which is used for nondestructive detection and real-time monitoring of the shear failure processes, is widely used in laboratory tests and field microseismic monitoring. AE parameters, such as AE counts, hits, energy, and events, have been used to quantitatively analyze shear failure processes. For example, Hong et al. [11] investigated the effect of shear on the AE characteristics of a rock–concrete interface. They found that the locations of AE sources are distributed over the entire shear zone before the shear stress reaches the residual stage. Moradian et al. [12-13] corroborated the sufficient precision of the AE method in detecting shear failure along rock joints. Meng et al. [14-15] revealed that the AE characteristics of rock joints are significantly influenced by normal stress and shear rate. They also highlighted the importance of the AE technique in the assessment of the shear failure of rock joints. However, the aforementioned studies have mostly focused on the effect of shearing on the AE characteristics of joints under CNL...
conditions, where the normal stress acting on the joints remains constant during the shear process. For in-depth underground scenarios, the normal stress acting on the joints is dynamic and is influenced by the normal stiffness imposed by surrounding rock blocks [16-17]. To date, few studies have investigated the effect of the normal stiffness imposed by the surrounding blocks on the AE characteristics of joints during the shear process.

Figure 1. Scanning graphs of the joint surface.

In this study, direct shear tests were conducted on rough-walled joints under various normal stiffness conditions using a servo-controlled shear testing apparatus. The effects of the normal stiffness on the shear behavior and asperity damage characteristics were studied, and the corresponding AE characteristics were analyzed.

Figure 2. Experimental setup.

2. Experimental setup

2.1 Specimen preparation

The artificial rock joint (composed of a mixture of high-strength plaster), water, and retardant with a mass ratio of 1:0.2:0.05 were used for the shear tests. The physical and mechanical properties of the rock-like material were reported by Zhang et al. (2020) [18], and are similar to those of the sandstone material. The specimen has a dimension of 200 × 100 × 100 mm³. The surface of the rock joint was measured using a three-dimensional (3-D) laser scanning profilometer system, as shown in Fig. 1. The joint roughness coefficient (JRC) of the joint was calculated in the shear direction, and the average JRC value of the joint surface was determined as 7.36.
2.2 Experimental apparatus and procedure
Shear tests under varying normal stiffness conditions were conducted using a servo-controlled direct shear apparatus at Nagasaki University, as shown in Fig. 2. The maximum applied load was 200 kN in the shear and normal directions with a precision of 99%. The shear displacement and normal displacement were measured using linear variable differential transformers (LVDTs) with a precision of 0.001 mm. The maximum shear displacement and normal displacement were 20 and 10 mm, respectively. The servo-controlled direct shear apparatus can automatically reproduce CNL and CNS boundary conditions with good precision. More details of this direct shear apparatus can be found in Jiang et al. (2004) [16].

In the shear tests, the AE was monitored with an 8-channel PAC system (Fig. 2). Four PICO AE sensors, 5 and 4 mm in diameter and height, respectively, were attached to the lateral side of the specimen. The distribution of the AE sensors is shown in Fig. 3. The frequency of the sensors range from 200 to 750 kHz, and the sampling rate was set to 1 million samples per second. The amplification of the preamplifier was set to 40 dB. The AE system and shear load were simultaneously triggered to ensure that the shear process was synchronized with the AE detection process. Direct shear tests were conducted under an initial normal stress level of 2 MPa with normal stiffness of 0, 1, 3, and 5 mm/MPa. The joints were sheared at a rate of 2 mm/min, and the maximum shear displacement was 10 mm, which is 5% of the length of the specimens.

![Shear stress vs. shear displacement](image1)

![Normal displacement vs. shear displacement](image2)

![Normal stress vs. shear displacement](image3)

**Figure 3.** Shear behavior of fracture G3 under various normal stiffness conditions: (a) Variation of shear stress with shear displacement, (b) Variation of the normal displacement with shear displacement, and (c) Variation of normal stress with shear displacement.

3. Mechanical behavior
The shear behavior of joints under different normal stiffness conditions is represented in Fig. 3. For the CNL conditions ($k_n = 0$ mm/MPa), the curve of shear stress versus shear displacement exhibited a three-stage behavior. First, at the beginning of the shear, the shear stress sharply increases linearly with the shear displacement until the peak shear strength is attained. Then, the asperities that constrain the movement of the joints were sheared off and the shear stress rapidly increased. The curve displayed
stress-softening behavior. Finally, a gradual decline in shear stress to the residual stage occurs. For the CNS conditions, the shear stress behavior was dependent on the normal stiffness. In the pre-peak stage (the point of shear stress with a sharp change in curvature was defined as the shear strength), the shear stress curves exhibit a near-identical shear behavior to the shear behavior of joints under the CNL conditions. In the post-peak behavior, the shear behavior is dependent on the normal stiffness. The test results showed a stress softening behavior under low normal stiffness conditions (i.e., \(k_n = 1 \text{ MPa/mm}\)). However, the application of higher normal stiffness conditions reduced the tendency of stress softening and encouraged a stress hardening effect. The peak shear stress for the joint under the CNL conditions is greater than that under the CNS conditions due to the shear contraction-induced decrease of the normal stress. In this study, the point of shear stress with a sharp change in curvature was defined as the peak shear stress.

\[\text{Shear displacement (mm)}\]

\[\text{Shear stress (MPa)}\]

\[\text{Cumulative AE count} (\times 10^4)\]

\[\text{Cumulative AE count} (\times 10^6)\]

**Figure 4.** Variation of AE count and cumulated AE count of joints under different normal stiffness conditions: (a) for \(k_n = 0\), (b) for \(k_n = 1 \text{ MPa/mm}\), (c) for \(k_n = 3 \text{ MPa/mm}\), and (d) for \(k_n = 5 \text{ MPa/mm}\).

Fig. 3(b) shows the variations in the normal displacement as a function of the shear displacement for joints under different normal stiffness conditions. At a limited shear displacement, the normal displacement decreased to a negative value due to the deformation of the asperity and the surface interlocking effect. Thereafter, the increasing rate decreases by abrading of the small rough asperities on the surface of large asperities. The continuous increment of the shear displacement leads to the shearing-off and crushing of some asperities, and small changes in the normal displacement were also observed. The normal displacement under the CNS conditions was observed to be smaller than that under the CNL conditions. This observation is reasonable because the shear-induced dilation increases the normal stress, which then decreases the normal displacement. The ultimate dilation was more under the CNL condition than the CNS condition and decreased as the normal stiffness increased. The decline in the ultimate dilation is due to the higher normal stress under large of normal stiffness conditions causing more significant asperity damage. Fig. 3(c) shows the variation in normal stress with shear displacement. The normal stress remains constant under the CNL condition during the shear process. Under such conditions, the normal stress curves are similar to those subjected to the normal
displacement under the CNS condition because the variation in normal stress is proportional to the change in the normal displacement.

Figure 5. Variation of AE energy rate and accumulated AE energy of the joints under different normal stiffness conditions: (a) for \( k_n = 0 \) MPa/mm, (b) for \( k_n = 1 \) MPa/mm, (c) for \( k_n = 3 \) MPa/mm, and (d) for \( k_n = 5 \) MPa/mm.

4. AE characteristics

AE is the transient elastic wave within a material caused by the rapid release of localized stress energy. Each AE signal corresponds to a failure or rupture event. Based on the definition of AE and results from previous studies, the AE count denotes a small-scale joint in the rock. The AE energy parameters (energy rate and cumulative energy) in an AE system represent the relative energy or intensity of the AE count, which is defined as the area enclosed by the signal envelope (unit of voltage is mv) and the axis of the abscissas (unit of time is \( \mu s \)) with a unit of mv·\( \mu s \).
increase, fracture subjected to ms, indicating that the level of er different ore).

investigations: conditions to investigate the shear behavior and AE

In this study, direct shear tests were conducted on plaster replica joints under CNL and CNS boundary conditions to investigate the shear behavior and AE characteristics of rock fracture subjected to different normal stiffness conditions. The following primary conclusions were drawn from these investigations:

1. The peak shear stress did not show clear tendencies relative to the normal stiffness, while the post-peak shear behavior was found to be dependent on the normal stiffness. When the normal stiffness was low, the stress softening behavior of the shear stress was observed, during which the shear stress decreased after attaining a peak value. Furthermore, as the normal stiffness increased, the stress hardening behavior of the shear stress was observed, which is characterized by a gradual increase in the shear stress with increasing shear displacement.

2. The normal stiffness has a major influence on AE characteristics. The evolution of the AE signals
showed the same trend at the pre-peak stage: a slow increase in the initial shear and rapid growth in the intermediate shear. For the post-peak stage, the AEs were more active under the CNS boundary conditions, and the cumulative AE values significantly increased due to more significant asperity damage caused by the high normal stress. Additionally, total AE events tend to increase with an increase in the normal stiffness.

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