Research Article

A Comparison of Mechanical Properties and Failure Processes of Saturated and Unsaturated Slate from Sichuan-Tibet Plateau Area, China

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Water content significantly affects the physical and mechanical properties of rock and can cause rock mass to become unstable. This, in turn, can cause geologic disasters such as water inrush and surrounding rock deformation. Uniaxial compression experiments on slate samples drilled from the surrounding rock of a tunnel in the Chinese Sichuan-Tibet Plateau area were performed coupled with acoustic emission (AE) monitoring. The changes in mechanical properties and failure processes of unsaturated and saturated slates were investigated comparatively through test results. Phenomena of a slight drop of $\sigma_1$ in the compaction and elasticity stage were observed, and it is due to the sliding of slate along the layered surface. According to the results, the average compressive strength of saturated slates was reduced by 24.3% compared to the unsaturated slates. The spatiotemporal evolution characteristics of AE indicated that the deformation and fracturing of unsaturated slates happened concentratedly and violently in the accelerated crack growth stage, while that of saturated slates occurred with low energy and uniform distribution spatially and temporally in the whole process. Moreover, water content reduced the brittleness index of unsaturated slate by 17.1%. For both conditions, the abundance of AE activity before failure shifted from a high level to a low level and lasted until failure. This can be used as a preliminary failure prediction of slates.

1. Introduction

The Sichuan-Tibet plateau area is located in the compression zone between the Eurasian and Indian plates, with intense geological plural form and high ground stress (the maximum measured value exceeds 50 MPa) throughout the region. The surrounding rock of many engineering structures often suffers from instability and failure due to this geological setting. Moreover, many railway tunnels in this area are deep buried in the subsurface and below the groundwater level. Their surrounding geology is typically comprised of slate. Therefore, studying the mechanical properties and instability failure process of slates in unsaturated and saturated states is vital for preventing tunnel surrounding rock disasters.

Slate in the Sichuan-Tibet line of China is often affected by groundwater, highly anisotropic, and in a high-stress state. In terms of mechanical properties of slate, research on deeply buried carbonaceous slate found that its mechanical parameters overall increase with an increase in confining pressure, although the existence of water reduces its cohesion [1]. Stoeckhert et al. [2] conducted tensile fracturing
tests on slate and sandstone and found that anisotropic slate tensile fracturing produces a complex crack morphology. Several others have conducted further studies on the physical and mechanical properties of slate influenced by its anisotropy [3–6], and a series of results have shown that its weak structural plane greatly affects the mechanical properties such as compressive strength, tensile strength, and shear strength. The anisotropy of slate is related to the orientation of constituent minerals formed under high temperature and high pressure [7, 8]. Nevertheless, the influence of bedding planes on stability and the deformation and fracture process of slate under loading are still not clear.

Several studies have been performed on the deformation and failure of rocks in various experimental settings, including compressive strength, tensile strength, fracture toughness, elastic modulus, and Poisson’s ratio [9–12]. The basic performance indicators of rock, especially in wet conditions, have also been extensively studied. In general, water reduces the friction coefficient and cohesion between mineral particles and changes the mineral composition and microstructure of rock, resulting in increased porosity and deterioration of its mechanical properties. The influence of water on rocks is a complex physical and chemical process.

In some cases, chemical dissolution can promote the formation of rock pores [13, 14]. With an increase in the water content or saturation time of a rock, the basic mechanical properties of the rock have been shown to reduce to varying degrees [15, 16]. Moreover, the water content also affects fracture propagation mechanisms of most rocks, which affects the mechanical stability of a rock mass [17–19]. These studies indicate that the water content has a significant impact on the microstructure and physical-mechanical properties of rocks. However, the impact on slate properties has rarely been analyzed.

Rock brittleness is an essential mechanical property and has become a novel research area, as brittle failure in the form of spalling or slabling is a possibility in deep underground engineering [20–23]. In general, brittle rocks commonly exhibit certain unique characteristics, such as sudden failure with the occurrence of tensile/shear fractures, causing a significant decrease in strength with slight inelastic strain [24, 25]. In the previous research, many have indirectly defined rock brittleness by using different methods [26, 27], other researchers have studied the rock properties of brittle failure in laboratory tests [28, 29]. Several studies have proposed evaluation indices of rock brittleness. The indices based on strength characteristics [30], full stress-strain curve characteristics [31], and energy characteristics [18, 32] are the most widely used. Generally, many rocks show brittle behavior, and it is the primary concern during the construction of underground engineering.

While considerable research has been conducted on the strength, softening properties, and microstructure of slate, there are insufficient data on analyzing the influence of water on the mechanical properties of deeply buried slate. Overall, the failure processes and physical-mechanical properties of unsaturated and saturated slate in the Sichuan-Tibet Plateau region still need to be further analyzed and discussed. It is critical for engineering capabilities to study the instability and failure prediction of saturated slate since the surrounding rock of many engineering structures is often in contact with groundwater and often suffers from the risk of instability and damage. Here, slate drilled from the surrounding rock of the Sichuan-Tibet Plateau area in China is subjected to uniaxial compression mechanics experiments in both saturated and unsaturated conditions using an AE method to monitor the samples during the loading process. The analysis of mechanical characteristics and failure process of slate provides a reference for disaster prediction during construction, operation, and maintenance of many projects in the Sichuan-Tibet Plateau region in China.

2. Experimental Process

2.1. Samples Preparation. The samples were taken from the Sichuan-Tibet Plateau region in China, as shown in Figure 1(a). Mostly belonging to the Upper Triassic Yajiang Formation or the Upper Triassic Lianghekou Formation, the slate in this area is dark gray, with metapelitic, silty, and tabular structure (Figure 1(c)). From X-ray diffraction tests on rock powder (Figure 1(b)), it was found that the minerals of carbonaceous slate are mainly quartz (grain size less than 0.05 mm), dolomite, sericite (grain size less than 0.03 mm), and albite low in proportions of 34%, 11%, 44%, and 11%, respectively. Distinct bedding structures were observed on the surfaces of drilled cores. The bedding planes of every rock sample were between 70° and 85° from the horizontal, which is consistent with the field investigation results.

According to the recommendations of the International Society of Rock Mechanics, the surfaces of the samples were polished and processed into a standard cylindrical specimen with a diameter of 50 mm and a height of 100 mm, as shown in Figure 1(a). Five unsaturated and five saturated samples were used in this experiment. Slate samples in a natural state were immersed in water for 48 hours to thoroughly saturate. The basic parameters of the size and test density of the samples are shown in Table 1. It is worth noting that unsaturated rocks denote natural slate rock cores obtained from the site, without any treatment.

2.2. Test Procedure. Uniaxial compression and AE monitoring were used to monitor the failure of the samples. The uniaxial compression loading tests were performed on the MTS815 Flex Test GT rock mechanics test system at the Key Laboratory of Deep Earth Science and Engineering of the Ministry of Education, Sichuan University. Six PCI-2 cards (totally 12 acquiring channels and 8 were used) from Physical Acoustics Corporation (PAC) was used for AE monitoring. The Nano-30 miniature AE sensor is adopted to detect AE signals. It has a resonant response at 300 kHz and a good frequency response over the range of 125–750 kHz, and its diameter is 0.312 ft. Totally, eight AE sensors were arranged on the surface of the rock sample, and four sensors were evenly distributed, respectively, at the upper and lower ends of the sample, as shown schematically in Figure 2.

In order to ensure the coupling effect between the test piece and the sensors, an appropriate amount of Vaseline was applied to the contact surface between the rock and the ring. The MTS815 Flex Test GT rock mechanics test system was used to perform the tests. The Nano-30 miniature AE sensor was used to detect AE signals. The test was performed under a load of 5 MPa to stabilize the load and prevent the sample from being broken during the test.
was applied on the surface of the sensors, and the two end faces of a specimen were polished to eliminate the interference of signals generated during the initial loading. Under uniaxial compression, the displacement loading mode was adopted with a loading rate of 0.04 mm/min, and the AE threshold was 30 dB. The AE monitoring system collected and calculated the AE energy, counts, frequency, amplitude, space coordinates, and other parameters.

2.3. Data Processing Method. To study the deformation and failure processes of rocks during loading, the stress-strain curves were divided into five stages according to previous researches [33–36]: (I) crack compaction, (II) linear elastic deformation, (III) crack initiation and steady propagation, (IV) specimen damage and unstable crack growth, (V) specimen failure and postpeak deformation, based on multiple laboratory experiments. Accordingly, to analyze and discuss the mechanical and deformation properties of slate temporarily and spatially, the failure process in the present study was divided into the five stages based on the stress-strain curves and characteristic stresses: \( \sigma_{cc} \) (crack closure stress), \( \sigma_{ci} \) (crack initiation stress), \( \sigma_{cd} \) (crack damage stress), and \( \sigma_p \) (peak stress). Figure 3 shows the determination of the characteristic stresses and division of five stages. The stress corresponding to the first zero of the crack volumetric strain-axial strain curve is the crack closure stress (\( \sigma_{cc} \)). The inflexion points on the crack volumetric strain-axial strain curve and volumetric strain-axial strain curve correspond

### Table 1: Size and density information of slate samples.

| Condition | Sample number | Height (mm) | Average (mm) | Diameter (mm) | Average (mm) | Density (g/cm\(^3\)) | Average (g/cm\(^3\)) |
|-----------|---------------|-------------|--------------|--------------|--------------|----------------------|----------------------|
| Unsaturated | 65-1          | 100.30      |              | 48.74        |              | 2.81                 |                      |
|           | 65-2          | 100.07      |              | 48.71        |              | 2.82                 |                      |
|           | 65-3          | 100.06      | 100.14       | 48.71        | 48.70        | 2.82                 | 2.81                 |
|           | 66-4          | 100.02      |              | 48.64        |              | 2.81                 |                      |
|           | 67-1          | 100.24      |              | 48.70        |              | 2.80                 |                      |
|           | 66-2          | 100.12      |              | 48.70        |              | 2.81                 |                      |
|           | 66-3          | 100.03      |              | 48.66        |              | 2.81                 |                      |
| Saturated | 77-1          | 100.11      | 100.10       | 48.51        | 48.59        | 2.80                 | 2.80                 |
|           | 77-2          | 100.13      |              | 48.57        |              | 2.79                 |                      |
|           | 77-3          | 100.13      |              | 48.53        |              | 2.80                 |                      |

Figure 1: (a) Slate cores and samples, (b) X-ray diffraction test results, and (c) the polarization microimage.
the crack initiation stress ($\sigma_{ci}$) and the crack damage stress ($\sigma_{cd}$), respectively.

To analyze AE characteristics and failure processes of slates, AE parametric method is adopted in the study, which reflects the behavior characteristics of a rock sample, and is widely used in the research field of internal damage and failure behavior of various rock materials [37–40]. In this paper, parameters including the cumulative counts (the number of oscillations across the threshold signal), counts rate, AE energy (area under the envelope of event signal detection), energy rate, and AE impact number were used to analyze the AE characteristics of slates during uniaxial compression. The AE count reflects the frequency of AE events. AE energy refers to the relative value of energy released by an AE event. AE count and energy together reflect the strength and frequency of AE events during the deformation and destruction of slate.

3. Results and Analysis

3.1. Strength and Deformation Characteristics. Through the processing of uniaxial compression experimental data, the basic mechanical parameters such as strength, Young’s modulus ($E_{av}$), and Poisson’s ratio ($\mu_{av}$) of slate were calculated and are shown in Table 2.

It can be seen from Table 2 that the compressive strength of slate in an unsaturated condition is between 27.34 and 58.09 MPa, with an average of $43.07 \pm 11.88$ MPa (11.88 is the standard deviation). The compressive strength of slate in a saturated condition ranges from 25.79 and 41.33 MPa, with an average of $32.59 \pm 6.52$ MPa. Compared with the unsaturated state, the mean compressive strength and $E_{av}$ of slate in a saturated state are reduced by 24.3% and 16.6%, respectively. $\mu_{av}$ in a saturated state increased by 34.6%. Water-rock physical and chemical reactions occur on the surfaces of the mineral particles resulting in a
decrease in the cohesion and friction coefficients between mineral particles. The mineral composition and microstructure also change, resulting in the formation of pores, dissolution cracks, etc. [41–43]. The joint action of the above factors causes a deterioration of rock strength. For slate, there are layered weak surfaces in the structure and the softening caused by water may also reduce the strength.

3.2. Failure Process and Acoustic Emission Characteristics. In this paper, the curves of AE characteristic parameters varying over time of all unsaturated and saturated slate samples were plotted, and the AE spatial evolution images during the entire loading process were drawn. Due to space limitations, only some typical images are shown here (Figures 4, 5 and 6).

(I) Crack compaction: when the stress is below $\sigma_{cc}$ (20% of the peak stress $\sigma_p$), the internal pores and microcracks gradually compact and close. The AE activities of slate in an unsaturated and saturated state are relatively quiet and not obvious. The compression closure of the microcracks primarily occurs inside the rock samples during the compaction stage, leading to microscale events, some of which have not yet reached the AE threshold value. This is also the reason that the AE signal does not appear during the initial compaction stage but appears later during the compaction stage for a short period (Figure 4, area I). The AE characteristics of slate during the compaction stage are also different between unsaturated and saturated states. The AE activity of the unsaturated slate is stable and quiet throughout the entire compaction stage (Figure 4(a), area I), while the cumulative ring time curve (Figure 4(b), area I) of the saturated slate shows a peak in the initial stage but decreases in the later stage of compaction, indicating that new microcracks are forming inside the rock sample at this moment. Overall, there are more high-energy AE events unevenly distributed along the upper and lower ends (Figure 6, area II). This is because the deterioration of the rock due to water also reduces the ability of the internal structure of the sample to bear pressure or tension. Therefore, under lower stress levels in the later stage of elasticity, the crack initiation and local expansion appear to occur within the internal structure.

(II) Linear elastic deformation: when the stress ranges from $\sigma_{cc}$ to $\sigma_{cl}$ (20% to 55% of the peak stress $\sigma_p$), the stress-strain curve is an oblique straight line, and the elastic deformation of the rock sample can be restored. There is a significant difference between unsaturated and saturated slates in the elastic deformation stage. The number of AE events in the unsaturated slate is still low and mainly consists of low-energy small-scale events (Figure 4(a), area II, and Figure 6(a), area II) while the AE activity of the saturated slate increased significantly in this stage (Figure 4(b), area II and Figure 6(b), area II). At the end of the elastic phase, both the counts and energy rates have small peaks (Figure 4(b), area II, and Figure 5(b), area II), indicating that new microcracks are forming inside the rock sample at this moment. Overall, there are more high-energy AE events unevenly distributed along the upper and lower ends (Figure 6, area II). This is because the deterioration of the rock due to water also reduces the ability of the internal structure of the sample to bear pressure or tension. Therefore, under lower stress levels in the later stage of elasticity, the crack initiation and local expansion appear to occur within the internal structure.

(III) Crack initiation and steady propagation: when the stress range is $\sigma_{cl}$ to $\sigma_{cl}$ (55% to 80% of the peak stress $\sigma_p$), microcracks start to appear in the rock sample. The initiation and propagation of microcracks are relatively stable until a large crack is formed inside, and even a certain degree of fracturing occurs, resulting in a small drop of stress. In the unsaturated and saturated conditions, the overall trends of AE events occurring are similar, with both slowly increasing. There is a peak at the beginning of this stage in AE events, after which the AE activity transitions to a higher activity rate. However, there are apparent differences between the unsaturated and saturated slate samples. The energy release of the unsaturated slate tends to be low at this stage (Figure 4(b), area III). Comparatively, the peak energy release of the saturated slate appears at this stage, and a large amount of energy released accounts for about 75% of the whole process (Figure 5(b), area III). These characteristics

| Condition     | Sample number | Peak strength (MPa) | Average (MPa) | Peak strain (%) | Average (%) | $E_{av}$ (GPa) | Average (GPa) | $\mu_{av}$ | Average |
|---------------|---------------|---------------------|---------------|----------------|-------------|-------------|---------------|-------------|--------|
| Unsaturated   | 65-1          | 42.24               |               | 0.50           |             | 10.78       |               | 0.10        |        |
|               | 65-2          | 27.34               |               | 0.46           |             | 9.54        |               | 0.20        |        |
|               | 65-3          | 50.56               | 43.07         | 0.58           | 0.66        | 9.74        | 9.45          | 0.12        | 0.16   |
|               | 66-4          | 58.09               |               | 0.98           |             | 9.31        |               | 0.23        |        |
|               | 67-1          | 37.10               |               | 0.78           |             | 7.81        |               | 0.16        |        |
|               | 66-2          | 26.76               |               | 0.65           |             | 5.57        |               | 0.24        |        |
|               | 66-3          | 36.25               |               | 0.92           |             | 7.58        |               | 0.20        |        |
| Saturated     | 77-1          | 25.79               | 32.59         | 0.38           | 0.59        | 8.76        | 7.87          | 0.21        | 0.22   |
|               | 77-2          | 41.33               |               | 0.56           |             | 8.55        |               | 0.25        |        |
|               | 77-3          | 32.84               |               | 0.45           |             | 8.88        |               | 0.19        |        |

Table 2: Basic mechanical parameters of slate samples.
Figure 4: Typical AE ring count and stress curves under unsaturated (a) and saturated (b) conditions.

Figure 5: Typical AE energy and stress curves under unsaturated (a) and saturated (b) conditions.

Figure 6: Spatiotemporal evolution process.
indicate that the initiation of new cracks and the propagation of macroscale cracks occur earlier in saturated slate than in unsaturated slate. This differs from findings on limestone, where it was observed that the peak AE activity of saturated rock samples occurred later than that of the dry rock samples [44]. In limestone, it was thought that the water softens the rock, which leads to a decrease in the cohesive force between the structures, which then leads to creep of the sample and a delay in the peak AE. This is contrary to the results of the two states of slate in this study. Here, water has a different influence on the properties of slate compared to limestone. Slate is a foliated metamorphic rock. Water has a series of physical and chemical reactions with the internal structure and minerals of slate, dissolving the soluble matter, thus producing more pores and softening the internal rock skeleton. It is then more likely to form cracks or propagate existing cracks, rather than the occurrence of creep such as in limestone under stress. Concurrently, a large amount of energy is released in case of severe damage of slate.

(IV) Specimen damage and unstable crack growth: when the stress range is $\sigma_{cd}$ to $\sigma_p$ (80% to 100% of the peak stress $\sigma_p$), new cracks quickly form, and the existing cracks continue to grow until the rock sample reaches its ultimate compressive capacity. The AE activity of slate in unsaturated state enters an active period with increasing cumulative counts and a large amount of energy released (Figures 4 and 5(a), area IV). The number of large events suddenly increases, and the internal activity of the rock sample is intense. The spatial distribution of AE forms two obvious structures (Figure 6(a), area IV), and obvious structural planes are formed on the lower side. This spatial distribution corresponds to the macroscopic cracks and fracture surfaces after failure (Figure 7). At the beginning of this stage, the stress of the unsaturated slate suddenly decreases, accompanied by the release of energy, which accounts for 85% of the entire loading process and indicates the occurrence of strong crack propagation. The unsaturated slate shows obvious brittleness in the prepeak stage.

Meanwhile, the AE activity of the saturated slate is relatively stable (Figures 4 and 5(b), area IV). After the energy has undergone accumulation and release during the previous stage, only a small amount of energy is released at this stage. The propagation and penetration of internal secondary cracks and the cracks are much less compared to the previous stage. These cracks develop into macro cracks when approaching peak stress.

(V) Specimen failure and postpeak deformation: when the load increases to reach its peak load, the slates begin to fail. The typical specimen images and schematics after failure is shown in Figure 7. When the load reaches the peak value for the unsaturated slate, it suddenly loses stability, and the stress-strain curve falls in a straight line. The saturated sample shows a gradual decrease in the bearing capacity, as indicated by a step-by-step decline in the stress-strain curve. At the same time, the AE system detected active AE signals, including significant AE events, energy, and counts (Figure 6). It shows that before the instability failure, there is minor microfailure in the unsaturated slate. The number of AE events, energy, and counts of the saturated slate is relatively stable throughout the entire loading process, which is due to the continuous occurrence of microdamage in the saturated slate. Therefore, it can be concluded that the progressive damage characteristics of saturated slate are more evident than that of unsaturated slate.

The mechanical properties of slates in the two conditions also show differences in the total amount of AE parameters during loading, which can result in different construction mechanics responses in practical tunnel engineering. Table 3 shows the statistics on the cumulative counts number and energy of AE during the slate loading process.

![Figure 7: Representative images and schematics of slate after the destruction: (a) unsaturated, mainly of main fractures, and (b) saturated, mainly of partial fractures.](image-url)
Table 3: Average AE cumulative counts and average energy statistics during loading.

| Condition   | Cumulative counts (10^4 times) | Accumulated energy (9.31 × 10^{-16} J) |
|-------------|--------------------------------|----------------------------------------|
| Unsaturated | 2.96                           | 56.95                                  |
| Saturated   | 2.12                           | 5.88                                   |

The cumulative counts number and cumulative energy of the saturated slate are significantly lower than the unsaturated slate. According to the previous analysis of the loading stages, the AE activities in unsaturated slate mainly occur during the accelerated crack propagation stage to rock sample failure, with little to no AE events during the other stages. This indicates that the occurrence of damage and fractures in unsaturated slate are centralized, explosive, and instantaneous when reaching a certain point of loading. In the construction of tunnel engineering, this characteristic may lead to sudden instability failure of the surrounding rock, as noted in several tunnel excavations. For example, the surrounding rock lithology surrounding parts of the Jiangmula tunnel (in China) in the Lhasa-Nyingchi line is a flysch suite (FW) phyllite intercalated with slate and sandstone. And there is no sign of groundwater activity. After excavation or even during construction, large-scale surrounding rock instability, falling blocks, collapses, and other adverse geological phenomena occurred; the falling rock blocks are relatively large [45]. The lithology surrounding a transverse section of the Dapingshan tunnel (in China) on the Chengdu Kunming line consists primarily of slate, metamorphic sandstone, and phyllite, all of the working face was dry. The vault and sidewall collapsed after excavation [46].

From the AE monitoring and stress-strain curve, the water-saturated slate has obvious, slight failure before complete failure. Instability occurs as the load increases to the peak value, showing a gradual failure process. At the same time, the cumulative value of the AE parameters of saturated slate is less than that of unsaturated slate, indicating that the degree of slate failure is reduced by water saturation. It is precisely because of the water saturation that the slate is characterized by progressive failure rather than abrupt failure. The tunnel along the Sichuan Tibet railway is deeply buried, and the surrounding rock is in a state of extremely high stress. Under the compression of high stress, the time-dependent fracture characteristics of a water-saturated slate can easily cause long-term deformation of the surrounding rock. For example, the Muzhailing tunnel [47], Lanjiayan tunnel [1], and Zhegushan tunnel [48] have been built in slate strata, some sections of the three tunnels are located below the groundwater level. And extensive deformations of the surrounding rock were encountered during construction, and cracking of the primary support and secondary lining occurred.

3.3. Brittleness Characteristics under Unsaturated and Saturated Conditions. From the results in Section 3, we found that the brittle properties of unsaturated and saturated slates are obviously different. Brittleness is a term commonly used in rock engineering applications to identify the possible failure characteristics of the rock mass [49]. Therefore, quantitative brittleness evaluation indicators were adopted to further study and discuss the brittleness of unsaturated and saturated slate. As is expounded in Introduction section, there exist many brittleness indices proposed previously. Among which brittleness evaluation indices based upon energy can better reflect the essence of brittle rock fracturing, since the deformation and failure process of rock under loading is essentially a process of energy release and dissipation [50]. Therefore, in this paper, the brittleness evaluation method, based on the energy evolution throughout the failure process, proposed by Chen et al. [51] was adopted for further analysis and discussion. The accuracy of this brittleness index was verified through laboratory tests on limestone and sandstone and can analyze the influence of different lithology, confining pressure, and water pressure on the brittleness of rock. It is suitable for this study and can accurately reflect the deformation and failure process of slate subjected to high ground stress and water saturation.

This method established a prepeak brittleness index $BE_{pre}$ and postpeak brittleness index $BE_{post}$, respectively. Here explaining the calculation method of the indices. Figure 8 exhibits the energy transformation throughout the rock failure process. The area of $S_1$ represents part of the dissipated energy transformed by the work done by the external force at the peak stress $\sigma_p$. Area $S_2$ represents the elastic strain energy that can be stored at the peak stress $\sigma_p$. The amount of $S_3$ and $S_4$ represents the input energy or the work that external forces do on the rock. $S_3$ is the increase of mechanical work done by the external force after the peak stress. $S_4$ is the residual elastic energy inside the rock at the state of residual stress, and $\sigma_r$ is the residual strength of the rock.

$S_1$, $S_2$, $S_3$, and $S_4$ can be determined as follows:

$$S_1 = \int_0^{\varepsilon_p} \sigma_p d\varepsilon_1 - S_2$$

(1)

$$S_2 = \frac{\sigma_p^2}{2E}$$

(2)
Table 4: Calculation results of energy and brittleness indices.

| Condition | Sample | \( S_1 \left(10^{-3}\text{J}\cdot\text{cm}^{-3}\right) \) | \( S_2 \left(10^{-3}\text{J}\cdot\text{cm}^{-3}\right) \) | \( S_3 \left(10^{-3}\text{J}\cdot\text{cm}^{-3}\right) \) | \( S_4 \left(10^{-3}\text{J}\cdot\text{cm}^{-3}\right) \) | \( BE_{\text{pre}} \) | \( BE_{\text{post}} \) | \( BE \) |
|-----------|--------|-----------------|-----------------|-----------------|-----------------|-------------|-------------|-----|
| Unsaturated | 65-1   | 27.27           | 82.70           | 0.88            | 48.53           | 0.75        | 0.97        | 0.86 |
|           | 65-2   | 30.82           | 62.70           | 5.30            | 29.61           | 0.58        | 0.71        | 0.65 |
|           | 65-3   | 2.10            | 131.17          | 16.50           | 49.24           | 0.98        | 0.83        | 0.91 |
|           | 66-4   | 6.27            | 181.10          | 50.15           | 7.59            | 0.97        | 0.78        | 0.87 |
|           | 67-1   | 11.97           | 85.67           | 6.94            | 56.72           | 0.88        | 0.81        | 0.84 |
| Average   | —      | —               | —               | —               | —               | 0.83        | 0.82        | 0.83 |
| Saturated | 66-2   | 6.60            | 64.28           | 15.08           | 26.71           | 0.91        | 0.71        | 0.81 |
|           | 66-3   | 8.55            | 86.75           | 90.42           | 4.57            | 0.91        | 0.48        | 0.69 |
|           | 77-1   | 6.77            | 37.89           | 23.79           | 8.04            | 0.85        | 0.56        | 0.70 |
|           | 77-2   | 15.15           | 99.86           | 27.47           | 47.20           | 0.87        | 0.66        | 0.76 |
|           | 77-3   | 27.48           | 58.51           | 49.08           | 22.19           | 0.68        | 0.43        | 0.55 |
| Average   | —      | —               | —               | —               | —               | 0.84        | 0.57        | 0.70 |

\[
S_3 = \int \frac{\varepsilon_1}{\varepsilon_i} \sigma_1 d\varepsilon_1 \quad (3)
\]

\[
S_4 = \frac{\sigma_4^2}{2E} \quad (4)
\]

When the rock reaches peak stress under the action of an external force, part of the work done by the external force is converted into irreversible dissipated energy. The remaining energy is converted into recoverable elastic energy, which is stored in the rock and provides energy for rock failure [50]. Rock brittleness is characterized by the aggregation ability, and then show a higher brittleness level. However, the average brittleness of slate is 0.83 ± 0.09 and 0.57 ± 0.12, indicating that the elastic energy used to maintain crack propagation after peak stress. A higher \( BE_{\text{post}} \) value indicates a higher level of brittleness exhibited during failure.

For the comprehensive consideration of prepeak and postpeak brittleness indices, a brittleness evaluation method that can reflect the entire process of stress-strain was developed, as follows:

\[
BE = \frac{BE_{\text{pre}} + BE_{\text{post}}}{2} \quad (7)
\]

According to the experimental data, the energy values represented by \( S_1 \), \( S_2 \), \( S_3 \), and \( S_4 \) are calculated first, and then the brittleness indices \( BE_{\text{pre}} \), \( BE_{\text{post}} \), and \( BE \) of unsaturated and saturated slate were obtained accordingly, as shown in Table 4.

According to the prepeak brittleness index \( BE_{\text{pre}} \), the average brittleness of slate is 0.83 ± 0.17 and 0.84 ± 0.09 under unsaturated and saturated conditions, respectively. The elastic energy storage rate, the ratio of the elastic energy \( S_2 \) to the input energy \( S_1 + S_3 \), of unsaturated slate is greater, indicating that more energy can be provided for the postpeak failure of rock samples and enhancing the ability of postpeak crack propagation. However, the \( BE_{\text{pre}} \) values for both the saturated and unsaturated slates are relatively high and similar, indicating that the dissipated energy for crack propagation and damage before the peak stress is far less than the stored elastic energy. Overall, they show a similar brittleness factor. The postpeak brittleness index \( BE_{\text{post}} \) of the unsaturated slate is generally greater than saturated slate (with an average value of 0.82 ± 0.09 and 0.57 ± 0.12, respectively), showing that the brittleness of slate after the peak is significantly reduced by water saturation by 30.7%. However, the average \( BE_{\text{post}} \) value of the postpeak saturated slate is 0.57 ± 0.12, indicating that the elastic energy used to maintain crack propagation after the peak accounts for only half of the total energy required for postpeak rock failure. At this time, more energy is needed to promote the failure of the rock sample. Therefore, the postpeak stress does not drop significantly, and the slate exhibits a much lower brittleness characteristic. \( BE \) characterizes the brittleness of slate.
throughout the entire stress and strain process. The $BE$ values of unsaturated and saturated slate are 0.83 ± 0.10 and 0.70 ± 0.10, respectively. Throughout the whole process, the brittleness of saturated slate is less than that of the unsaturated slate by approximately 15.0%.

The quantitative analysis results are consistent with the qualitative analysis based on the schematic diagram of stress-strain curves (see Figure 9 for typical stress-strain curves of two conditions): The postpeak stage of axial stress-strain curves in unsaturated conditions is steep, showing complete brittle failure characteristic; While that in saturated condition appears gentle stages after the peak. Unsaturated slate undergoes a progressive failure, and displays semi-brittle deformation accompanied by stress degradations.

In summary, the presence of water greatly reduces the brittleness of slate. In the prepeak stage, the energy storage capacity ($S_2/(S_1 + S_2)$) of slate is reduced when saturated, which leads to a decrease in the energy needed to provide crack propagation and spontaneous fracturing. In the postpeak stage, the mechanical energy provided by external force decreases the proportion of dissipated elastic energy, which weakens the failure ability of saturated slate and shows weaker brittleness. Combined with the analysis of the failure process of slate in Section 3.2, due to the relatively high brittleness of unsaturated slate in tunnel construction, adverse geological phenomena such as block falling and collapse at different scales are prone to occur. Due to the water softening effect, the saturated slate is prone to sustained time-dependent deformation, which leads to large deformation disasters.

4. Discussion

4.1. Failure Mechanism of the Stress Drops. During the compaction stage and elastic deformation stage, crack propagation rarely occurs. When loading and unloading in these two stages, the rock will undergo recoverable elastic deformation. However, for slate, a stress drop phenomenon is sometimes observed (Figure 9). Specimens 65-3, 66-2, and 77-1 experienced stress drops to 18.7% and 22.2% peak strength levels, respectively, resulting in irreversible deformation. This is different from most results reported on other rock types in the compaction stage and elastic deformation stage in previous studies. Triaxial or uniaxial compressive tests on granite [52], limestone [53], coal [54] and other rocks [55, 56] show that the stress-strain curves in the two stages are normally smooth and straight, and the deformations are typically slight and consistent.

In order to explore the internal mechanisms of a rock sample during stress drop, the AE spatial location images during the stress drop period were drawn and compared with the photos of rock samples after failure (Figure 9). AE events had planar distribution in the rock specimens, with an angle between the plane and the horizontal of 71°. Photographs after rock sample tests showed that the friction slip generated at the bedding surface of rock during the stress drop eventually extended throughout the sample and formed a corresponding fracture surface.

Previous studies have shown that bedding planes have an evident influence on the mechanical strength and failure mechanisms of rock. Simpson et al. [57] studied the effect bedding has on crack initiation and crack propagation on the Mancos Shale using the Brazilian disc test. The study showed that the sample’s failure mode depends on the angle between its bedding plane and the loading direction. [58, 59] studied the failure track of shale with bedding planes, divided the failure track into three types, and determined the failure mechanism. However, the slate in this study was taken from the stratum of a tunnel. The angle between the
fracture surface of the slate formed during the stress drop and the horizontal direction is about 71° (Figure 9), which is precisely the bedding plane angle of the underlying slate of this tunnel. Therefore, the stress drop is caused by local slip failure along the slate bedding surface during the loading process. The bedding structure of the slate influences its mechanical properties, and low-level stress can cause crack propagation or slippage along the bedding plane. In engineering design and construction, rock anisotropy represented by weak structural planes should be considered [60, 61]. For instance, the Zhegu Mountain tunnel is mainly composed of thin slates or carbon slates. Throughout the construction process, it has encountered typical buckling failure of the sidewall caused by the thin slate layer bending under the high geo-stress leading to the large deformation and collapse [1, 62]. At the Muzhailing Tunnel in the Lanyu railway, the thickness of a single layer of the carbonaceous slate varies around 2-10 cm and caused excessive deformation during excavation [63, 64] pointed out that large deformation with a small angle will occur when the tunnel axis intersects with the rock plane at a small angle. Consequently, the angle between the slate bedding plane and the tunnel axis in tunnel construction is vital to avoid a large-angle intersection and reduce the risk of large deformation or collapse caused by sliding.

### 4.2. Prediction and Analysis of Instability and Failure

According to the spatial evolution characteristics (as shown in Figure 6), when the axial stress of the unsaturated slate reaches 80%, the number of AE events significantly increases and forms nucleation points. The opening and propagation rate of cracks inside the specimen is accelerating, and the AE energy is released in large quantities at this stage. This indicates that the high-energy AE events intensively occur during this stage, and the rock sample loses stability and fails near the peak bearing capacity. This can be used as a precursor criterion for the destruction of unsaturated slate. But for saturated slate, AE events are active in all stages of loading. It is difficult to predict the instability failure based upon the spatial location.

To further confirm the failure precursor information of both saturated and unsaturated slates, the characteristic phenomenon of AE time series parameters and energy release before failure were studied. The AE parameters reflect the processes of initiation, propagation, and fracture of internal cracks under load. Figure 10 shows the prepeak characteristic points, and relevant reflecting information, and Table 5 lists the stress levels of the points.

In Table 5, the "relative maximum prepeak ring rate points" are defined to represents the peak counts rate in the ring rate cluster formed nearest to the peak stress. The AE time series characteristics of unsaturated and saturated slates near destruction show common features (See Figures 4 and 5), that is, AE activity before failure has experienced a process from high level to a low level and lasted for a period of "low AE period" until failure.

It can be seen from Figure 10 and Table 5 that the maximum value of the AE parameter mostly occurs in the unstable crack growth stage after an 80% stress level; a large number of cracks expand, converge, and nucleate during this stage. The results in Table 5 also show that the stress level at the relative maximum prepeak cumulative counts rate point (σRRmax) is consistent and representative among all specimens. The average stress levels of unsaturated and saturated states are 90.1% and 92.4%, respectively. After this point, AE activity enters a low-level, active state until peak stress is reached. The average duration of the low AE period is 42.75 s and 29.78 s, respectively. The AE activity in an unsaturated state of the hypor AE lasts longer. When the slate reaches 90% of the peak stress, the AE activity is high, and the counts rate appears as a cluster peak until the AE activity turns to a continuous low-level state. This indicates
Table 5: AE time series parameters and average stress levels at characteristic points.

| Parameter                                                                 | Unsaturated | Saturated |
|---------------------------------------------------------------------------|-------------|-----------|
| Maximum increase point of prepeak accumulated energy ($\sigma_f/\sigma_p \times \%$) | 66.24       | 65.47     |
| Maximum slope point of prepeak counts curve ($\sigma_{R_{max}}/\sigma_p \times \%$) | 83.45       | 73.83     |
| Maximum prepeak counts rate point ($\sigma_{R_{max}}/\sigma_p \times \%$)       | 88.95       | 68.40     |
| Relative maximum prepeak counts rate point ($\sigma_{R_{max}}/\sigma_p \times \%$) | 90.10       | 92.40     |
| Duration time of the low AE period (s)                                   | 42.75       | 29.78     |

instability and damage of the sample, which can be used as the Sichuan-Tibet line area precursor judgment information of surrounding rock failure. The instability of surrounding rock is affected by many factors, such as rock type, microstructures, and excavation disturbance. Therefore, in an actual project, the occurrence environment, stress characteristics, and disturbance of surrounding rock should be fully investigated. Combined with on-site monitoring data and AE failure precursor information, the instability and failure of surrounding rock could be comprehensively predicted.

5. Conclusion

In this study, uniaxial compression experiments, and AE monitoring experiments of slate from the Sichuan Tibet Plateau were performed, respectively, in saturated and unsaturated conditions, and the mechanical properties, AE characteristics, and instability precursors of slate under saturated and unsaturated conditions were studied. The main conclusions are as follows:

(1) Water saturation weakens the mechanical properties of slate and reduces the brittleness of slate. The compressive strength and elastic modulus of saturated slate are 24.3% and 16.6% lower than unsaturated slate, respectively. The brittleness index of unsaturated slate and saturated slate are 0.83 ± 0.10 and 0.70 ± 0.10, respectively, 15.0% greater than saturated slate

(2) The failure property of slate changes from brittle to brittle-plastic due to water saturation. AE activity of unsaturated slate is mainly concentrated during the stage of accelerated crack growth. AE activity of saturated slate occurs throughout the entire loading process, and the accumulation of AE parameters of saturated slate is much lower than that of unsaturated slate

(3) The stress drop phenomenon is observed in both saturated and unsaturated slates in the pore fissure closure and elastic deformation stage, which is due to the sliding of slate along the layered surface. From the final failure track, the foliation structure of the slate plays a dominant role in the complete failure of slate. Therefore in the engineering construction, when tunnels pass through the slate surrounding rock stratum, the axis of tunnel intersecting with the slate at a large angle should be avoided to prevent the surrounding rock sliding along the slate surface, causing instability

(4) The comprehensive analysis based on AE time and space evolution characteristics show that the prediction point of instability of unsaturated slate is about 90% of the peak load. The prediction point of the instability and failure of the saturated slate is about 92% of the peak load

Data Availability

Data are available on request.

Conflicts of Interest

No conflict of interest exists in the submission of this manuscript.

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