Experimental Study on Acoustic Emission Characteristics of Intermittent Jointed Rock Mass Under Uniaxial Compression

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Abstract. Using large size of intact and intermittent jointed rocks made with equivalent materials, the stress-stain curves, ringing counts and energy accumulation of acoustic emission (AE) were obtained by AE monitoring in real time under uniaxial compression. The strength, deformation, progressive failure evolution and AE properties of two kinds of rock samples were compared. Through the analysis of AE parameters, the results indicate that the sudden increase of AE ringing counts and AE energy may be utilized as precursor information for the failure of rocks. AE location may directly reflect the dynamic evolvement process of rock cracks. Unlike the failure of intact rock sample, the AE ringing counts and energy curves of jointed rock sample show obvious multi-peaks, and the final peak appears behind the stress peak. The failure mode of intact rock is mainly vertical tensile breakage, whereas the tensile wing crack propagates through the joint surface, resulting in the failure of jointed rock sample.

Keywords: jointed rock mass; acoustic emission; uniaxial compression; crack propagation

1. Introduction

As the main objective of underground engineering research, rock mass undergoes various tectonic processes in the long geological history and forms structural planes such as joints, fissures, bedding and fault fracture zones in geo-stress field. The existing structural planes result in the complex mechanical properties of the rock mass structure such as heterogeneity, discontinuity and anisotropy, which may greatly reduce the overall strength of the rock mass. These structural planes bring potential risk to the safety of underground rock engineering. Therefore, it is of great theoretical and practical significance to study the mechanical properties and failure evolution characteristics of jointed rock mass under compression.

Scholars have made some achievements in the mechanical properties and failure mechanisms of jointed rock mass from the perspectives of theoretical analysis, experimental investigation and numerical simulation. Shen et al. [1] studied the failure mechanism of fractures and rock bridges of two types of prefab cracks similar materials specimens under uniaxial compression, the results showed that the different fracture geometries produced significantly different stress, leading to the different failure modes. Bobet et al. [2] carried out uniaxial and biaxial compression experiments on the
similar materials specimens of prefab crack rocks, and studied the influence of the geometrical shape and stress of the crack on the crack propagation model and the failure characteristics. Tang et al. [3] performed numerical simulation for crack initiation, growth, coalescence and failure of different crack types of rock specimens under uniaxial compression, the results were in good agreement with experimental observations. Chen et al. [4-5] systematically studied the effects of joint group and joint connectivity on the strength, deformation and the fracture characteristics of jointed rock mass under uniaxial compression.

During the failure of rock mass under compression, the internal microcracks initiate and continuously expand, accompanied by the intense energy release, the transient elastic wave, namely, acoustic emission, occurs in rock mass. Acoustic emission technology has been accepted and widely used in civil, water conservancy and petroleum engineering in recent years. Compared with other monitoring methods, acoustic emission technology can continuously monitor the internal damage during the process of rock deformation. As an effective method, it has been applied into various fields such as rock mass damage, internal crack evolution and fracture for many other materials. Mansurov et al. [6] studied the acoustic emission characteristics of microcracks accumulation and breakthrough cracks in the process of rock failure, and predicted the type of failure according to the acoustic emission characteristics. Chang et al. [7] defined the damage thresholds before the peak strength of rock under triaxial compression by the moving point regression technique using acoustic emission data. Shkuratnik et al. [8] analyzed the characteristics of acoustic emission parameters in different deformation stages, and proposed that acoustic emission characteristics are related to the internal structure of rock samples. Through triaxial loading and unloading test of specimens with different rock bridge lengths, Chen et al. [9] studied the acoustic emission characteristics of rock bridge failure process under different stress paths and confining pressures. Li et al. [10] performed the acoustic emission localization test of granite under uniaxial compression. and studied the space-time evolution and failure precursor.

Currently, acoustic emission monitoring technology is mainly utilized in the detection of fracture in small-scale specimen model or surface crack of rock mass. However, the study of internal micro-crack propagation with acoustic emission for large-scale specimen model test is rarely reported. This paper aims to perform acoustic emission monitoring test accompanied by uniaxial compression for intact and jointed rock mass made with equivalent material. The counts, energy accumulation, localization and evolution of acoustic emission events and the failure modes between two rocks are systematically compared.

2. Acoustic Emission Tests for Jointed Rock Mass

2.1. Preparation of Jointed Rock Mass Specimens
The high strength cement, fine sand, water, silica fume and water reducer were mixed together to make the equivalent jointed rock mass and the reference ratio was 1:1.2:0.35:0.15:0.015[11]. The equivalent materials were weighted and mixed well in the mixer. Then, the mixed equivalent materials were poured in the mould in the dimensions of 100mm×100mm×200mm for vibration and standard curing. The intact rock specimens were made by directly removing the mould, as shown in Figure 1. In the process of pouring the jointed rock specimens, metal sheets with a thickness of 0.4mm were inserted in the mould with prepared gaps according to the designed geometric parameters in Table 1. After the equivalent material in the mould was maintained for 10 hours, the metal sheets were drawn out, and the specimens were maintained for 28 days. The jointed rock mass specimens with three sets of intermittent joints with the inclination of 30 ° were finally obtained after demolding (Figure 2).
Table 1. Geometrical parameters of jointed rock specimen

| Joint angle $\theta$ | Joint density $\rho$ | Joint length $d$ | Joint Persistency $k$ | Joint length $a$ | Bridge length $b$ |
|----------------------|----------------------|-------------------|-----------------------|------------------|-------------------|
| 30°                  | 3                    | 12                | 0.424                 | 15               | 20                |

2.2. Test Equipment and Scheme

The MTS647.250 electro-hydraulic servo-controlled material test system is adopted to perform the uniaxial compression test. It is composed of main machine, oil source, control system and loading frame. The maximum static and dynamic loading forces are 2750kN and 2500kN, respectively. The displacement control mode is adopted at a loading speed of 0.01mm/s or at a constant strain rate is $5 \times 10^{-5}$s$^{-1}$. PTFE films were placed on the contact position between specimen and two platens to diminish the end effect, (Figure 3).
The acoustic emission test adopts the Express-32 testing system using 6 channels with a sampling frequency of 5 MHz, and a threshold of 40 dB. The acoustic emission sensor is NANO30 with a frequency of 100–500 kHz, and the preamplifier gain of 40 dB. Vaseline was smeared on the contact positions between the rock sample and the sensors to ensure their coupling effect. The calibration and arrangement of the probe locations are shown in Figure 4.

![Figure 3. MTS647.250 material testing system](image)

![Figure 4. Probe locations of acoustic emission](image)

3. Test Results and Analysis

3.1. Comparison of Mechanical Properties of Intact and Jointed Rock Specimens

The complete stress-strain curves of intact and jointed rock specimens under uniaxial compression are shown in Fig.5. As can be seen from Fig.5, both stress-strain curves include the compaction stage, elastic deformation stage, plastic deformation stage and the residual strength stage. In the initial compaction stage, the primary microcracks in the specimens close with the increase of axial stress. In
In the elastic stage, there is almost no generated cracks inside the rock corresponding to the linear portion of the stress-strain curve. As the stress keeps increasing, the irreversible plastic deformation occurs in the plastic deformation stage. Meanwhile, a large number of new micro-cracks and joints form and expand rapidly in the rock specimens, resulting in brittle failure. It seems that the jointed rock specimen exhibits more obvious yield stage than the intact rock specimen ahead of the peak stress, which leads to the failure of the intact specimen at a relatively smaller strain. According to the uniaxial compressive- stress-strain curves, the elastic modulus, peak strain and the peak strength of intact and jointed rock specimens were obtained and listed in Table 2.

Table 2. Mechanical parameters of intact and jointed rock specimens

| Rock specimen       | Modulus of elasticity /GPa | Peak strain /% | Peak strength /MPa |
|---------------------|-----------------------------|----------------|-------------------|
| Intact rock specimen | 9.22                        | 0.81           | 66.8              |
| Jointed rock specimen | 9.20                       | 0.49           | 35.1              |

3.2. Comparison of Acoustic Emission Ringing Counts

The relationships of AE ringing count rate and the accumulated ring counts with real time of intact and jointed rock specimens are present in Figure 6.

As seen in Figure 6, for intact rock mass, the ringing count rate is low, and the cumulative ringing counts is relatively stable during the compaction and elastic stages, the ringing count rate fluctuates at a large amplitude in the plastic stage. A continuous nonlinear increase and a peak of ringing count occur. Succeedent brittle failure takes place whereafter the maximum ringing count. Then, the ringing count gradually decreases in the residual strength stage. For jointed rock specimen, the slope of accumulated ringing count curve increases slightly in the elastic stage. It is noticed that there is muti-peak of the AE count rate in the deformation process of jointed rock specimen. The corresponding accumulated AE counts increase rapidly during the plastic stage. The lag of the AE count behind the peak stress is due to the final macro-crack forms later then the stress reaches the peak. The ringing count gradually decreases and disappears after the major crack penetration.
3.3. Comparison of Acoustic Emission Energy

The relationships of energy rate and accumulated energy with time of intact and jointed rock specimens are shown in Figure 7. When compared to Figure 6, it is found that the changes in of corresponding energy rate or accumulative energy and ringing count rate or accumulative counts with time are nearly the same. Before the microcracks spread, there is almost no energy released from the rock specimen. During the unstable microcrack propagation, the acoustic emission events become active. The monitored energy increases sharply with the loading time, and the cracks rapidly expand until the failure of the specimen. For the jointed rock, the evolution of energy rate or energy accumulation with time is consistent with that of ringing count or ringing count accumulation. There are three dramatic enhancements of released energy during the microcrack growth stage. The third peak of energy rate appears whereafter the peak stress. The slope of AE energy accumulation curve is larger than that of ring count accumulation curve implying that the AE energy increases much more significantly.

Figure 6. Relationships of AE ringing count rate and the accumulated ring counts with real time of intact and jointed rock specimens
Figure 7. Relationships of energy rate and accumulated energy with time of intact and jointed rock specimens

3.4. Acoustic Emission Event Localization

Figure 8 presents the acoustic emission event localizations of intact rock specimen. When 20% ~ 30% of the peak stress is loaded, the micro-cracks initiates, and the locations of acoustic emission events centralize at the bottom and the top of the specimen. As the stress increases up to 30%~60% of the peak stress, the micro-cracks at the bottom and the top expand to the middle “blank area”. When 60%~80% of the peak stress is loaded, the acoustic emission events further concentrated event clusters appear on the bottom surface of the specimen, indicating new cracks may have generalized on the lower plane. As the applied stress approaches to 80%-100% of the peak stress, the cracks at two surfaces of the sample spread and connect to the center. Crack penetration leads to the specimen fracture, as shown in Figure 9.
The acoustic emission localization in the fracture process of jointed rock specimen is shown in Figure 10. When 20% ~ 30% of the peak stress is loaded, the acoustic emission event localization appears sporadically along with the initial micro-cracks. The AE events are mainly near the bottom of the specimen and the prefab joints. When 30% ~ 60% of the peak stress is loaded, the acoustic emission events in the specimen further increase, and its concentration at joints becomes more evident. This demonstrates that the tensile airfoil microcracks form from the ends along the direction of the joint planes. As it reaches to 60%~80% of the peak stress, the acoustic emission events begin to concentrate at the bottom of the specimen, implying that breakthrough cracks may have happened at the bottom of the specimen. In the process of the applied stress increasing to 80%-100% of the peak stress, there is a remarkable increase in the acoustic emission events. Meanwhile, the tensile airfoil cracks spread downward until penetrate the specimen, as shown in Figure 11. It is worth noting that the crack initiation at the bottom of jointed rock specimen, the formation and penetration of the tensile airfoil cracks on the jointed surfaces correspond to the three peak values of characteristic parameters of the acoustic emission.
Figure 11. Failure mode of jointed rock specimen

4. Conclusions
The acoustic emission tests have been conducted to study the acoustic emission ringing count, energy rate and the failure evolution properties of intact and jointed rock specimens under uniaxial compression. The experimental results show that:

1. The AE count rate and energy rate contain abundant precursor information of progressive rock failure, which can be directly utilized in the prediction of rock breakage. Particularly, for the jointed rock, the sharp increase of acoustic emission parameters correspond to the forecasting rock fracture.

2. Different from the intact rock, the counting rate and energy rate monitored in real time of jointed rock exhibit obvious multi-peak phenomenon. The last peak value of the jointed rock lags behind its peak strength.

3. The evolution of acoustic emission event localization may directly reveal the formation, location and expansion of initial micro-cracks in rock specimens. The initial micro-cracks in intact rock specimen expand from the ends of the rock to the middle “blank area”. With an increase in loading force, the macro-cracks penetrate to “the blank area” and the splitting failure occurs. Unlike the intact rock, the acoustic emission events are densely located in the vicinity of joints. The initial micro-cracks evolve to form tensile airfoil cracks along the prefab joint planes until the rock fracture.

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