Acoustic Emission Characteristics and Energy Evolution of Granite Subjected to Uniaxial Compression

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Abstract. In order to obtain the precursory characteristics of rock dynamic disasters such as rock burst, based on effectiveness of energy evolution and acoustic emission detection method for rock failure prediction, mechanical parameters, acoustic emission signals and energy of granite under uniaxial loading-unloading cycles were studied by using GAW-2000 electrohydraulic servo rigid press machine controlled by computer and PCI-2 acoustic emission acquisition system. Peak strength of granite under cyclic loading and unloading decreased by about 18% compared with conventional static loading. Ringing count rate was characterized by interval between "sudden increase" and "relative calmness period" before peak strength and the "b" value continued to decrease and to the minimum before instability. Failure represented characteristics of "cracked by step expansion and multiple release of energy". Felicity ratio gradually declined with cycle numbers and it was an important parameter for evaluating rock damage. Containing energy level was used to express rock risk coefficient, accumulation energy was mainly dominant in the pre-peak strength and dissipative energy density was far lower than elastic energy density. Combination of acoustic emission characteristics and energy evolution can improve the accuracy of rock failure prediction.

1. Introduction
Initiation and expansion of cracks are caused by loading for brittle materials such as rock, accompanied by acoustic physical phenomena and releasing elastic stress waves at the same time, which is called acoustic emission phenomenon of rock [1]. The deformation and failure of granite under engineering disturbance is a very complex damage evolution process and the nature of rock failure is instability state driven by energy [2]. Rock failure is in the dynamic evolution of inputted, accumulation, dissipation and releasing, and the ratio of energy distribution is constantly adjusted with stress level. The development of fracture determines the energy evolution characteristics of rock. Many valuable achievements about acoustic emission characteristics and energy evolution before failure have been studied by domestic and foreign researchers. As for the precursory information of rock instability, many scholars [3-12] gave early warning from the aspects of frequentness and frequency-domain. The sudden increase of acoustic emission characteristic parameters and continuous occurrence of high-frequency signals can serve as precursors for rock imminent failure. In terms of energy, many scholars [13-16] believed that the energy evolution characteristics can accurately reflect crack development inside the rock and energy variation is the direct manifestation of internal structural adjustment.

However, at present, investigations on correlation between mechanical properties, acoustic emission and energy of granite are deficient. The purpose of this paper is to perform laboratory tests to
explore the energy distribution and acoustic emission characteristics at different stress levels. This paper also provides a theoretical basis for the analysis of dynamic disasters.

2. Rock Samples and Experimental Methods

All rock samples used in the tests are granite within -1236\(^\circ\) - - 1321m depth and were taken from the geological borehole of new main shaft in Xincheng gold mine, Shandong province. Standard cylindrical samples (50mm diameter×100mm length) were obtained through core drilling and sawing. NM-4B ultrasonic testing instrument was used to detect wave velocity of samples and samples with similar wave velocity were selected.

When the sample was in contact with the testing machine, the acoustic emission instrument and the testing machine were turned on at the same time. Acoustic emission parameters such as ring count and mechanical parameters were recorded with unified time unit. Uniaxial static loading was controlled by deformation with a speed of 0.02mm/min until failure. According to peak strength of uniaxial loading, the cyclic loading-unloading testing gradient was set at 30KN. Deformation control was adopted throughout the whole process, with loading speed of 0.02mm/min and unloading speed of 0.04 mm/min, loading paths were shown in Table 1.

| Samples | Loading methods       | Loading paths                  | Peak stress (MPa) | Average peak stress (MPa) |
|---------|-----------------------|--------------------------------|-------------------|--------------------------|
| H-1, H-5 | Conventional static loading | 0→Failure                     | 87.66, 91.06      | 91.06                    |
| H-2, H-3 | Cyclic loading and unloading | 0→30KN→5KN→60KN→5KN→90KN→5KN→120KN→5KN→Failure | 73.14, 72.59, 73.86 | 73.20, 73.86 |
| H-4     |                        |                                |                   |                          |

3. Testing results and analysis

3.1 Failure morphology and acoustic emission characteristics

The surface cracks of broken samples were obtained by using sulphate paper. Taking H-1 and H-4 as examples, H-1 with abundant cracks on the surface was dominated by tensile fracture, and H-4 with a small number of cracks around the main crack was dominated by transfixion shear fracture, shown in Figure 1 (a) and (b). The peak strength of cyclic loading and unloading was declined by about 18% compared with peak strength of uniaxial loading in Table 1. When the loading exceeds crack expansion stress, the damage of rock keeps accumulating with the increase of cycle times, resulting in the reduction of rock sample strength. Loading and unloading curve represents "inward concave" and keeps moving forward, as shown in Figure 2. The deformation when unloading to about 5KN is considered as irreversible deformation, irreversible deformation of H-3 with cycle times were 0.095mm, 0.104mm, 0.111mm and 0.117mm respectively, and the increment gradient were 0.009mm,
0.007 mm and 0.006mm respectively. The irreversible deformation increased with the number of cycles, but the deformation increment decreased. Rock with internal defects is an inhomogeneous material, closed original fracture gave rise to increase of elastic modulus and some cracks opened again after unloading, so the stress-strain curve showed an internal concave shape. When the loading exceeded maximal loading level of upper stage, the irreversible deformation continued to increase and the cracks expansion stress was improved by rock stiffness, while the irreversible deformation increment decreased.

Figure 2. Stress-strain curve of H-3    Figure 3. Stress-time-ring count rates-b value of H-1

Gutenberg and Richter conducted a statistical analysis of a large number of seismic activities and obtained the following relationship between earthquake magnitude and frequency[12]:

\[ \lg N = a - bM \]  

(1)

Where, M is the magnitude, N is the earthquake frequency within ΔM range, a and b are constant and b value is an important parameter to evaluate the seismic activity level in a certain region. In this paper, acoustic emission amplitude parameter is used to calculate b value. b value was calculated by using the least square method, and the amplitude interval was equal to 0.5. In order to avoid the experimental error caused by too few acoustic emission events at a certain stress level, this paper took 1000 acoustic emission events as a set of data and 100 acoustic emission events as sliding for calculation, and obtained the variation law of b value at different stress levels.

There must be a corresponding relationship between ringing count rate and b value. The variation law of stress-time-ringing counting rate-b value was showed in Figure 3.

Rock sample underwent four stages: initial cracks compactness (OA section), stable crack development (AB section), unsteady crack development (BC section) and failure after peak stress (CD section). Stress was manifested by the fluctuation rise of pre-peak and the step fall of post-peak, and there was a significant correspondence between mechanical parameters and acoustic emission characteristic parameters and b value. Ringing count rate is few in the compaction stage, which is characterized by initial calmness and b value rising. Contacting and friction of particles generated weak the acoustic emission signals and the fracture expansion level was low. Acoustic emission

Figure 4. H-1Stress-time-accumulated ring counts  Figure 5. H-3  Stress-time-accumulated ring counts

signals were continuous stabilization and weak in the elastic deformation stage, while b value
fluctuated within the range of 1.4 to 1.6. The ringing count rate was featured by the interval between "sudden increase" and "relative calmness period" in the crack unsteady development stage. b value continued to decrease and showed a sharp decline at the sudden increase point of ringing count rate, which was the opposite with ringing count rate. Due to the unsteady expansion and interaction of cracks, acoustic emission signals were densely distributed and high intensity at high stress level. The stress level would decrease slightly and then continued to go up on account of the adjustment of the internal structure, and the obvious abnormal acoustic emission signals would be generated at stress adjustment point then entered relatively quiet stage, which is a continuous accumulation of elastic energy from the perspective of energy.

The sudden increase point corresponded to generate local transfixion crack in the rock sample. Instead of continuing to expand, the energy would continuously accumulate through the "relative quiet period" and when the energy demand of crack growth was further reached then sample would form a macro fracture inside rock. The intensity and density of acoustic emission signals were significantly enhanced and b value continued to decrease after failure. Rock has the ability to improve its bearing capacity through internal structural adjustment, but stress is rapidly declined due to internal irreparable damage occurring in the post-peak stage. Drastic structural variation and adjustment generated a large number of acoustic emission signals and each strong and dense acoustic emission signal could be regarded as the result of crack development and internal stress adjustment. Therefore, the continuous abnormal acoustic emission signal can be used as the primary criterion for samples to be destabilized, and the fast reduction of b value as the secondary criterion can improve the accuracy of predicting failure.

The cumulative ring count curve of two channels was showed in Figure 4, there was only a difference in number. Cumulative curve was manifested by step-up before pre-peak stage and the difference value of two channels gradually reduced in unstable development stage. The signal of high-frequency channel lagged behind low-frequency channel, indicating that friction and slippage between particles were dominated by low-frequency acoustic emission signals and high-frequency acoustic emission signals were generated by the mutual connection between cracks. The characteristics of interval between sudden increase and relative calmness stage, and step shape of cumulative ringing counting indicate that failure is characterized by progressive crack propagation and multiple energy releasing, and is the result of local crack developing to macro crack.

3.2 Kaiser effect
Kaiser effect refers to the ability of brittle materials such as rock to remember the maximum loading level. Obvious acoustic emission phenomenon appears before maximum loading, which is the Felicity effect. Felicity ratio[3]:

\[
FR_i = \frac{P_{i+1}}{P_{\text{max}}} 
\]

Where: FR\(_i\) is Felicity ratio for \(i\) cycle; P\(_{i+1}\) is the stress generating obvious acoustic emission signal in the \(i+1\) cycle; P\(_{\text{max}}\) is the maximum stress experienced by the \(i\) cycle.

Figure 6. Stress-accumulated ringing counts
Figure 7. Local magnification
There is a significant anti-Kaiser effect and Felicity ratio effect is strengthened with the increase of cycles and the accumulated ringing count increases rapidly at the same in Figure 6. The accumulative ring count develops in a straight line and increases slowly in unloading stage in Figure 7.

Felicity ratio gradually declined and the reduction rate increased as the number of cycles in Figure 8. It indicates that cycles give rise to accumulation damage and the memory of the rock becomes worse. Taking X-H-4 as an example, Felicity ratio was 0.91 at 21% relative stress level. Considering the testing error, it could be considered that rock sample has strong memory. Felicity ratio decreased from 0.91 to 0.83 at 42% relative stress, the rock sample was in the elastic development stage and still had strong memory. Felicity ratio decreased from 0.83 to 0.67 at 63% relative stress level, and the rock sample was in the stage of fracture expansion from stable to unstable. Felicity ratio decreased from 0.67 to 0.41 at 80% relative stress level. The crack developed rapidly and the damage increased sharply parallel to the loading direction. The loading required to reach the irreversible deformation in the previous cycle is significantly less than that in the previous maximum loading as. Acoustic emission signals are mainly related to loading stress level, and the irreversible deformation is the main reason for the Felicity ratio effect. Felicity ratio can reflect the internal structure adjustment and damage degree of rock, which is an important parameter to evaluate rock damage.

![Figure 8. Felicity ratio with cycles](image)

3.3 Energy evolution analysis

Elastic energy is mainly stored in the form of elastic strain and is reversible energy. Dissipative energy includes plastic deformation energy, surface damage energy, thermal energy, radiation energy and other forms, and is an irreversible energy. It is unrealistic to monitor each energy in the dynamic loading. From the perspective of the first law of thermodynamics and without considering heat exchange, the energy evolution during the loading is mainly represented by the dynamic balance of inputted total energy, elastic strain energy and dissipation energy[16], that is:

\[ U = U_e + U_d \]  

(3)

Where, \( U \) is the inputted total energy of testing machine, \( U_e \) is the elastic strain energy and \( U_d \) is the dissipative energy.

Brittle rocks such as granite have inherent properties of storing external energy through deformation, which is defined as self-storage energy rock mass. Elastic strain energy stored at peak strength is defined as self-storage energy limit. The ratio of elastic strain energy to self-storage energy limit under the current stress level is defined as rock energy level. The law of rock energy level with stress is shown in FIGURE. 9. At the initial loading stage, the energy storage is less at the low energy level. The containing energy level at the peak strength is defined as 1, and the containing energy level fluctuates between 0 and 1 during whole loading process. The energy level represents risk coefficient and inputting less energy will exceed the bearing limit of rock sample when energy level is closed to 1. Energy stored inside rock needs to be converted into fracture damage energy, fragment kinetic energy and other energy, thus causing severe rock damage.

In order to describe the evolution law of energy distribution, the ratio of elastic energy density to inputted energy density is defined as the self-storage energy ratio, which is used to represent the
energy storage characteristics under different stress states. The ratio of dissipated energy density to
inputted energy density is defined as the energy dissipation ratio, which is used to represent the energy
consumption features under different stress states and reflect intensity of internal structural
adjustment.

Rock sample was in the elastic development stage within 21%-42% stress level in Figure 10 and
elastic strain energy density and self-storage energy ratio increased linearly, while the dissipation
energy density increased slowly. Rock was at the end of elastic development stage within 42%-63%
stress level and accumulated energy was still the main factor. Sample was about to enter the unstable
development stage of cracks within 63%-84% stress level. The non-uniform development of partial

4. Conclusion

(1) The interval between sudden increase and relative calmness period of ringing count rate appear in
the non-stable development stage, and the strong abnormal acoustic emission signals can be used as
the primary criterion for failure of rock samples. Rapid reduction of b value as the secondary criterion
can improve the accuracy for prediction.

(2) The cumulated ringing count is characterized by step-shape rising before peak strength and the
ringing counts of high frequency channel obviously lags behind the low frequency channel. The
frictions and slippage between particles are dominated by low-frequency acoustic emission signals,
while the initiation and transfixion between cracks are dominated by high-frequency acoustic emission
signals, representing the characteristics of progressive expansion of cracks and multiple energy
releasing.

(3) Felicity ratio effect is obviously enhanced with the increase of cycles, which can be used as an
important parameter to evaluate rock damage. Damage is mainly concentrated in the loading stage and
the accumulated ringing count in the unloading stage develops almost in a straight line.

(4) The concepts of containing energy level, self-storage energy limit, self-storage energy ratio and
self-dissipation energy ratio are proposed to characterize energy storage characteristics, storage limit,
elastic strain energy and distribution law of dissipation energy respectively.

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