Study on Acoustic Emission Characteristics and Damage Evolution of Shale under Uniaxial Compression

Dongqiao Liu¹, Zeli Wang¹,², Yunpeng Guo¹,², Jie Sun¹,² and Hehe Liu¹,²

¹State Key Laboratory for Geomechanics & Deep Underground Engineering, China University of Mining and Technology, Beijing, 100083, China

²School of Mechanics and Civil Engineering, China University of Mining and Technology, Beijing, 100083, China

E-mail address: guoyunpeng@student.cumtb.edu.cn; ORCID: 0000-0001-9946-7505

Abstract: In this study, uniaxial compression tests were conducted and acoustic emission monitoring technology was used on shales from the Liutang Village, Shizhu County, Chongqing City. The ringing count and energy evolution law during the compression process of shale samples were analyzed, and their damage evolution characteristics are discussed. The results show that the cumulative ringing count and cumulative energy curves of acoustic emission can be used to distinguish among crack closure, stable crack propagation, and unstable crack propagation. According to the change process of acoustic emission events, the damage evolution process of shale samples is divided into damage maintenance, initiation, and acceleration. The constitutive model established based on the acoustic emission ringing count can better describe the uniaxial compression process of shale samples.

Key words: Shale; Uniaxial compression; Acoustic emission; Damage evolution

1 Introduction

Shale gas is a substitute for conventional natural gas. Recently, exploring and exploiting shale gas has
attracted attention. China is rich in shale gas resources and has great potential for exploitation, but it is in its infancy, and many problems must be solved urgently\cite{1}. The damage evolution process of shale is related to safe shale gas mining. Studying the damage evolution process of shale will help reveal its failure mechanism in practical engineering, providing safety guarantees for shale gas mining in our country.

Acoustic emission (AE) refers to the phenomenon that a material deforms or breaks when it is stressed and releases strain energy in the form of elastic waves\cite{2}. As an accompanying phenomenon during the rock deformation and failure process, the AE signal contains rich information, such as defects and changes in the behavior of the internal structure of rock materials\cite{3,4}. Many scholars have used AE technology to conduct numerous indoor uniaxial and triaxial compression test studies on brittle materials, such as rock and concrete\cite{5-9}. The results show that AE technology is effective for studying the damage and failure characteristics of rock materials. During rock compression deformation and failure, a few AE signals are generated during the compaction stage, elastic deformation stage, and the early stage of elastic–plastic deformation. The AE phenomenon mostly occurs during the late elastic–plastic deformation and post-peak violent failure stages.

Numerous theoretical studies have been conducted on the rock damage evolution law and constitutive model based on AE characteristics. Ohtsu\cite{10} used the rate process theory to apply AE to the damage assessment of concrete and proposed that the AE activity was positively related to the number of cracks in the material. Heiple et al.\cite{11,12} conducted several experimental analyses and proposed that the AE ringing count can better reflect the material’s internal damage evolution process. Tang and Xu\cite{13} used the continuous damage mechanics method to obtain a damage model of rock material based on AE parameters under uniaxial compression from a mesolevel perspective. Some domestic scholars have used AE to study the damage and failure characteristics of rocks, such as coal, limestone, sandstone, salt rock, and shale. They revealed the AE characteristics during rock deformation and failure processes and established the stress–strain–damage evolution model of AE characteristics\cite{14-18}.

In this study, a uniaxial compression test was conducted on shale from the Liutang Village, Shizhu County, Chongqing City. Combined with an AE monitoring system, AE characteristics during the process of shale compression failure were analyzed, and the damage evolution law was discussed.

### 2 Shale Uniaxial Compression Acoustic Emission Test

#### 2.1 Sample Preparation and Test Equipment

The rock used in the experiment was taken from the outcrop shale of the Maxi Formation in the Liutang Village, Shizhu County, Chongqing City, which was brownish red. The main mineral components were quartz (45.1%) and clay minerals (21.52%). The plagioclase (11.59%) and dolomite (8.69%) contents were low, with an average density of 2.57 g/cm$^3$ and an average longitudinal wave velocity of 3.18 km/s.
According to the standard recommended by the International Society of Rock Mechanics\cite{19}, the sample was processed indoors into a standard cylindrical sample with a diameter of 50 mm and a height of 100 mm (Fig. 1).

![Fig. 1. Images of prepared rock specimens.](image1)

A uniaxial compression test was conducted using the true triaxial test system (Fig. 2), independently developed at the State Key Laboratory for Geomechanics and Deep Underground Engineering of the China University of Mining and Technology (Beijing). The test was controlled by displacement. The loading rate was 0.004 mm/s, which stopped after the specimen was destroyed. The AE test of rock samples adopts a Micro II acquisition system that can collect AE signals during the test process in real-time. The probe adopts a nano-30 sensor with a threshold value of 40 dB. To ensure full contact between the AE probe and sample surface, apply an appropriate amount of Vaseline coupling agent on the probe. Simultaneously with the compression test, start AE monitoring and record data. Figure 3 shows a diagram of a uniaxial compression AE test.

![Fig. 2. True triaxial experimental system.](image2)

![Fig. 3. Diagram of acoustic emission (AE) test with uniaxial compression.][20]
2.2. Test Results and Analysis

Basic mechanical properties of shale

Limited by space, three representative groups of shale test results were selected for analysis, and Figure 4 shows the uniaxial compression full stress–strain curve. Young’s moduli (GPa) of the three rock sample groups are 7.13, 8.26, and 7.42, respectively.

As shown in Figure 4, the entire process of stress deformation and failure of shale samples can be divided into three stages. 1) Compacting stage—during the initial loading stage, the initial microcracks, micropores, and cracks in the shale are gradually compressed and closed under pressure, and the curve is a gentle slope and concave. 2) Elastic deformation stage—after the rock’s internal fractures are compacted and closed, the rock transforms from a discontinuous medium to an approximate continuous medium; here, almost no crack initiation or even propagation of rock microcracks occur. 3) Elasticity plastic deformation and failure stage—when the compressive stress exceeds the elastic limit (yield point), new microcracks are gradually formed inside the rock, and the original cracks gradually begin to expand. The rock experiences nonlinear and plastic deformation but is still dominated by elastic deformation. When the internal microfracture surface of the rock is fully developed, some microcracks begin to penetrate, and the macrocracks penetrate the core. The rock is instantly damaged and the strength drops rapidly.

Analysis of Acoustic Emission Characteristics

The AE ringing count refers to the number of rectangular pulses exceeding the preset threshold voltage in the ringing waveform of an AE signal. AE energy refers to the area enclosed by the event signal detection envelope. Lockner, Perera et al, and Khazaei et al found that the change in the characteristics of AE ringing and energy counts during rock compression deformation and failure can reflect the initiation, expansion, and penetration of the microcracks in the rock. Therefore, this study analyzed the AE ringing count and energy changes under uniaxial compression of shale samples.
(1) Features of acoustic emission ringing count

Based on the analysis of the shale stress–strain-cumulative ringing count curve (Fig. 5), the internal crack change of the rock sample during the compression process can be divided into crack closure, stable crack propagation, and unstable crack propagation and coalescence failure stages. 1) The crack closure occurs during the initial compaction stage of the rock. Initial defects, such as cracks and pores, shrink and close under pressure. Here, the AE signals are less because of the closure of the cracks inside the rock and the frictional activities along the crack surface. The cumulative ringing count is at a low level.

2) With an increase in axial load, new microcracks and microdamages are generated in the rock. The original microcracks steadily expand and the AE ringing count slowly increases, but it is still at a low level, belonging to the quiet period of AE. 3) Many new microcracks appear in the unstable propagation stage of cracks. The microcracks are fully developed. Some microcracks begin to penetrate through irregular development, the AE signal becomes active, and the AE ringing count grows exponentially. The rock produces macroscopic cracks and destruction.
Fig. 5. The cumulative ringing count acoustic emission (AE) releases with axial strain.

(2) Acoustic emission energy characteristics

AE energy is the energy released by crack initiation, development, and penetration during uniaxial compression. The accumulated energy can reflect the overall trend of the energy released by the rock under uniaxial compression. Likewise, according to the previous division method, the process is divided into three stages for analysis and research (Fig. 6), and then the cumulative energy of each stage and total proportion are counted (Table 1).
As shown in Figure 6, the energy changes of different shale samples are similar. Limited energy release occurred from stage I to stage II, and the total cumulative energy accounts for <1%. During the third stage, numerous AE signals are generated, and the total accumulated energy in this stage accounts for >99%. The rock sample’s internal cracks are fully expanded and penetrated, and a macroscopic fracture surface is formed.

**Fig. 6.** Relationship between acoustic emission (AE) energy and time of the shale samples.

As shown in Figure 6, the energy changes of different shale samples are similar. Limited energy release occurred from stage I to stage II, and the total cumulative energy accounts for <1%. During the third stage, numerous AE signals are generated, and the total accumulated energy in this stage accounts for >99%. The rock sample’s internal cracks are fully expanded and penetrated, and a macroscopic fracture surface is formed.

**Table 1.** Statistical of acoustic emission (AE) energy of the shale samples.

| Sample No. | Cumulative energy (aJ) and the total proportion(%) | Stage I | Stage II | Stage III |
|------------|-----------------------------------------------|--------|--------|----------|
| 1#         | Cumulative energy 44700 (The total proportion) (<0.01) | 68300  (99.98) | 1.56E8  (99.98) |
3 Damage Evolution Analysis

To further analyze the entire failure process of shale, the relationship between damage variables and AE parameters was established using continuous damage mechanics, and the damage evolution law during shale compression was described. Many studies have shown that the AE ringing count is proportional to the strain energy released by the dislocation movement, fracturing, and crack propagation in the material\cite{24}, which is one of the characteristic parameters that can better reflect the change in material properties. Therefore, the cumulative ringing count of AE was used to characterize the damage variables. The damage evolution law of shale can then be studied.

3.1 Establishing the Shale Uniaxial Compression Damage Model Based on Acoustic Emission Characteristics

Rabotnov\cite{25} first defined the damage variable as

$$ D = \frac{A - A_d}{A} = 1 - \frac{A_d}{A}, $$

where $D$ is the damage variable, $A_d$ is the effective bearing area after the rock sample is damaged, and $A$ is the initial cross-sectional area without damage.

Lemaitre\cite{26} created the strain equivalent hypothesis and established the damage constitutive model based on continuous damage mechanics under uniaxial compression.

$$ \sigma = E\varepsilon(1 - D), $$

where $\sigma$ is the effective stress, $E$ is the elastic modulus of the nondestructive material, and $\varepsilon$ is the strain.

If the cumulative AE ringing count for the complete destruction of the entire end face $A$ of the nondestructive material is $C_0$, then the AE ringing count for the failure of the unit area element $C_w$ is

$$ C_w = \frac{C_0}{A}. $$

When the section damage area reaches $A_d$, the cumulative AE ringing count $C_d$ is
\begin{equation}
C_d = C_w A_d = \frac{C_0}{A} A_d, \quad (4)
\end{equation}

giving

\begin{equation}
D = \frac{C_d}{C_0}, \quad (5)
\end{equation}

During the test, because of insufficient rigidity of the testing machine or different fracture conditions of the set rock samples, the rock is not always completely destroyed (i.e., the damage of the rock sample has not reached 1), and the testing machine stops working. Therefore, the damage variable is corrected to

\begin{equation}
D = D_U \frac{C_d}{C_0}, \quad (6)
\end{equation}

where \(D_U\) is the critical value of the damage, \(C_d\) is the cumulative AE ringing count to a certain moment, and \(C_0\) is the cumulative AE ringing count to the moment of rock failure.

Liu et al.\cite{14} normalized the damage threshold.

\begin{equation}
D_U = 1 - \frac{\sigma_c}{\sigma_p}, \quad (7)
\end{equation}

where \(\sigma_c\) is the residual strength and \(\sigma_p\) is the peak strength.

The expression of the damage variable based on AE parameters can be obtained using formulas (6) and (7)

\begin{equation}
D = \left(1 - \frac{\sigma_c}{\sigma_p}\right) \cdot \frac{C_d}{C_0}, \quad (8)
\end{equation}

According to reference\cite{27}, there is almost no new damage to the rock during the elastic deformation stage, wherein the damage degree of the entire stress–strain process is the smallest. Therefore, the study started from the elastic stage. The stress–strain curve of the shale uniaxial test was obtained from the right translation of the longitudinal axis to the intersection of the reverse extension line and the transverse axis during the elastic stage. It was set as the origin of the new coordinate, and its distance from the origin \(O\) of the original coordinate was \(\varepsilon_0\), based on AE. The characteristic uniaxial compression shale damage model is

\begin{equation}
\sigma = (1 - D)E(\varepsilon - \varepsilon_0) = \left(1 - D_U \frac{C_d}{C_0}\right)E(\varepsilon - \varepsilon_0). \quad (9)
\end{equation}

### 3.2 Damage Evolution Law

Table 2 shows the relevant parameter values of three shale sample groups. According to equation (8),
Figure 7 shows the typical shale strain-damage relationship curve. From equation (9), the damage variable value calculated using the cumulative ringing count of AE can be obtained. Figure 8 shows the obtained stress–strain and experimental curves. The two curves correlate well; therefore, the damage variable represented by the cumulative ringing count of AE is more reasonable.

| Sample No. | UCS (MPa) | Residual strength (MPa) | Young’s Modulus (GPa) | Intercept $/\varepsilon_0$ | Cumulative count $/C_0$ |
|------------|-----------|-------------------------|-----------------------|---------------------------|-------------------------|
| 1#         | 97.73     | 12.818                  | 7.13                  | 0.625                     | 159003                  |
| 2#         | 112.72    | 0.585                   | 8.26                  | 0.543                     | 22527                   |
| 3#         | 108.66    | 3.560                   | 7.42                  | 0.663                     | 59727                   |

(a) 1# shale sample

(b) 2# shale sample
It can be observed from Fig. 7 that the shale damage evolution process can be divided into three stages. 1) Damage maintenance stage—this is the crack closure and elastic deformation stages. The microcracks did not initiate or even expand, and the damage variable did not change. Here, the AE was inactive, and the ringing count of AE remained unchanged. 2) The initial stage of damage—this is the stage of microcrack generation and stable propagation. Here, the damage variable gradually increases. The AE activity began to be active, the AE ringing count increased gradually, and the AE energy increased gradually. 3) Damage acceleration stage—this is the accelerated crack propagation stage. The damage variable increases exponentially until the damage critical value. The original cracks in the rock sample continue to expand, and the new microcracks continue to produce. Finally, the macrocracks are formed by coalescence, and the rock sample is destroyed. Here, the AE activity is extremely active, and the AE ringing count and energy reach the maximum when the damage occurs.
Fig. 8. Comparison of theoretical stress–strain curve with the experimental one.

It can be seen from the evolution process of AE rock damage that the rock sample undergoes a gradual evolution process from generating cracks to expansion and then failure\cite{28}. From the initiation and stable expansion of microcracks to the unstable expansion of original cracks, the rapid generation of new cracks to the convergence and penetration of large-scale cracks occurs until many macrocracks appear, and the rock is finally destroyed. The rock damage variables characterized by the AE ringing count can better reflect the damage evolution law at each stage of the shale deformation and failure process.

4 Conclusions

The AE characteristics of shale under uniaxial compression were studied, and the damage evolution process of shale was analyzed.

(1) The full stress–strain curve of shale under uniaxial compression can be divided into initial compaction, elastic deformation, elastoplastic deformation, and failure stages.
(2) The AE information of shale during compression deformation and destruction is related to the initiation, development, and penetration of internal microcracks. During the initial compaction stage, elastic deformation stage, and the early phase of the elastoplastic deformation stage, almost no new cracks are generated or expanded. Therefore, the AE signal is weak. During the elastoplastic deformation and destruction stage, the AE signal increases sharply and the cumulative AE energy reaches the maximum at peak stress.

(3) By using the AE cumulative ringing count to characterize rock damage variables, a shale uniaxial compression damage evolution model was obtained. The shale damage evolution process can be divided into damage maintenance, damage initiation, and damage acceleration. The constitutive model of shale based on AE characteristics can better describe the stress–strain–damage process of shale.

Acknowledgements

Financial support from the National Natural Science Foundation of China (No. 41941018, No. 52074299) and Fundamental Research Funds for the Central Universities (No. 2021JCCXSB03).

References

[1] Chen S B, Zhu Y M, Wang H Y, et al. Research status and trends of shale gas in China. Acta Petrolei Scinica 31(4), 689–694(2010). (in Chinese)

[2] Qin S Q. An introduction to rock sound emission technology. Southwest Jiaotong University Press, (Chengdu)1993. (in Chinese)

[3] Lockner D A, Byerlee J D, Kuksenko V, et al. Quasi-static fault growth and shear fracture energy in granite. Nature 350(6313), 39–42 (1991).

[4] Lockner D A. The role of acoustic emission in the study of rock fracture. International Journal of Rock Mechanics and Mining ence & Geomechanics Abstracts 30(7), 883–899(1993).

[5] Su C D, Yu X X, Li B F, et al. Experimental study of acoustic emission characteristics during sandstone single-three-axis compression, Journal of Mining and Safety Engineering 28 (02), 225–230(2011). (in Chinese)

[6] Qin H, Huang R, Wang W Z. Study on the acoustic emission characteristics of different water-bearing coal rocks damaged by pressure deformation. Journal of Rock Mechanics and Engineering 31 (06), 1115–1120(2012). (in Chinese)

[7] Ming J. Damage evolution law based on acoustic emission and Weibull distribution of granite under uniaxial stress. Acta Geodynamica Et Geomaterialia 175(3), 1–9(2014).
[8] Sun X, Li Y B, Duan Y J, et al. Study on acoustic emission characteristics and damage evolution law under three-axis compression of North Mountain Granite, Journal of Rock Mechanics and Engineering 37 (S2), 4234–4244(2018). (in Chinese)

[9] Li Q, Li S T, Gao Y, et al. Analysis of damage evolution and acoustic emission during concrete single-axis compression. Journal of Shenyang University of Technology 42 (06), 687–693(2020). (in Chinese)

[10] OHTSU, Masayasu. Rate process analysis of acoustic emission activity in core test of concrete.[J]. Doboku Gakkai Ronbunshu, 1992(442): 211–217.

[11] HEIPLE C R, CARPENTER S H. Acoustic Emission from Dislocation Motion[M]. In: Acoustic Emission, New York: Gordon and Breach Science Publishers, 1983.

[12] WADLEY H N G, SC FUBY C B, SPEAKE J H. Acoustic Emission for Physical Examination of Metals. International Metals Reviews 25(1), 41–64(1980).

[13] Tang C A, Xu X H. Evolution and propagation of material defects and Kaiser effect function. Journal of seismological research, 1990.

[14] Liu B X, Huang J L, Wang Z Y, et al. Study on damage evolution and acoustic emission character of coal-rock under uniaxial compression. Chinese Journal of Rock Mechanics and Engineering 28(1). 3234–3238(2009). (in Chinese)

[15] Yang Y J, Wang D C, Guo M F, et al. Study of rock damage characteristics based on acoustic emission tests under triaxial compression. Chinese Journal of Rock Mechanics and Engineering 33(1). 98–104(2014). (in Chinese)

[16] Li S C, Xu X J, Liu Z Y, et al. Electrical resistivity and acoustic emission response characteristics and damage evolution of sandstone during whole process of uniaxial compression. Chinese Journal of Rock Mechanics and Engineering 33(01). 14–23(2014). (in Chinese)

[17] Zhou Z W, Liu J F, Zou H, et al. Acoustic emission characteristics and damage evolution of uniaxial compression salt rock. Journal of Yangtze River Scientific Research Institute 33(05), 63–68(2016). (in Chinese)

[18] Yao H Y, Chen J B, Nie X R, et al. Evolution of shale damage in uniaxial compression acoustic emission tests. Science Technology and Engineering 20(4), 1581–1586(2020). (in Chinese)

[19] FAIRHURST C E, HUDSON J A. Draft ISRM suggested method for the complete stress-strain curve for intact rock in uniaxial compression. International Journal of Rock Mechanics and Mining Sciences 36(3), 279–289(1999).
[20] Liu D Q, Wang Z, Zhang X Y, et al. Experimental investigation on the mechanical and acoustic emission characteristics of shale softened by water absorption. Journal of Natural Gas Science & Engineering, 2018: S1875510017304432.

[21] Lockner D. The role of acoustic emission in the study of rock fracture. International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts. Pergamon 30(7), 883-899(1993).

[22] Perera M S A, Ranjith P G, Viete D R. Effects of gaseous and super-critical carbon dioxide saturation on the mechanical properties of bituminous coal from the Southern Sydney Basin. Applied energy 110, 73-81(2013).

[23] Khazaei C, Hazzard J, Chalaturnyk R. Damage quantification of intact rocks using acoustic emission energies recorded during uniaxial compression test and discrete element modeling J. Computers and Geotechnics 67, 94-102(2015).

[24] Liu X W, Lin J Z, Yuan Z Y. Research on evaluation of material fatigue damage by acoustic emission technology. China Railway Science 18(4), 74-81(1997). (in Chinese)

[25] Rabotnov Y N. On the equations of state for creep. 1963.

[26] Lemaitre J. A continuous damage mechanics model for ductile fracture. Journal of Engineering Materials and Technology 107(1), 83-89(1985).

[27] Liu D Q, Li D, Zhang X Y. A new strain softening damage constitutive model for rocks based on defects growth. Chinese Journal of Rock Mechanics and Engineering 36(2), 3902-3909(2017). (in Chinese)