Hindawi
Geofluids
Volume 2022, Article ID 3280185, 10 pages
https://doi.org/10.1155/2022/3280185

Research Article

Study on the Precursors of Coal-Rock Fracture Based on the Maximum Lyapunov Exponent of Acoustic Emission Parameters

Guoqiang Cheng,[1] **Xiaohui Sun**,[1] **and Jiangong Li**[2,3]

[1]*School of Energy and Mining Engineering, Shandong University of Science and Technology, Qingdao 266590, China*
[2]*State Key Laboratory of Gas Disaster Detecting, Preventing and Emergency Controlling, China Coal Technology Engineering Group Chongqing Research Institute, Chongqing 400039, China*
[3]*State Key Laboratory of Coal Mine Disaster Dynamics and Control, College of Resources and Environmental Sciences, Chongqing University, Chongqing 400030, China*

Correspondence should be addressed to Guoqiang Cheng; skd991928@sdust.edu.cn and Jiangong Li; flyljg@163.com

Received 16 August 2021; Accepted 24 February 2022; Published 18 March 2022

Academic Editor: Na Huang

In this paper, the relationship between acoustic emission (AE) parameters and coal-rock fracture is investigated by using the discrete element particle flow simulation software PFC. PFC is used to simulate the coal-rock uniaxial compression test for extracting the time series of AE event number, calculate the maximum Lyapunov exponent of the time series, and analyze the chaotic characteristics of AE event number. Combined with the relationship between the maximum point of the Lyapunov exponent and the peak point of the stress-strain curve, the coal-rock fracture precursor model was developed. The results indicate that during the uniaxial compression of coal-rock, the number of AE events first increases and then decreases, while the maximum point appears after the peak point of the stress-strain curve. The lower the coal-rock homogeneity, the earlier is the initial occurrence time of AE events. The AE event number has chaotic characteristics. In most cases, the chaotic characteristics of the number of AE events are the most evident before the specimen is completely destroyed. When the maximum Lyapunov exponent of AE event number time series mutates, it indicates that the specimen is about to be destroyed entirely, which can be used as a precursor criterion for coal-rock fracture.

1. Introduction

When rocks are deformed or damaged under external forces, strain energy is released as elastic waves, which is termed acoustic emission (AE). AE has been widely used in rock stability monitoring and predicting mines, slopes, and tunnels since it was discovered in the 1930s.

AE signals can not only reflect the failure process of the rock but also indicate the characteristic information of the internal structure of the rock. Over the years, many researchers have studied the relationship between AE signal parameters and rock fracture, further explaining the mechanism of rock fracture and putting forward reasonable precursor criteria for rock fracture. Shkuratnik et al. [1] studied the AE characteristics of coal-rock fracture under different loading methods. Liu et al. [2] developed a coal-rock damage model based on the AE characteristics of coal-rock under uniaxial compression to reveal the damage evolution of coal-rock under load. Cao et al. [3–5] conducted uniaxial compression tests on rock specimens, using ringing count, main frequency and entropy values of AE signals, and AE energy rate as main characteristic parameters to predict rock fracture. Wang et al. [6] examined the rock critical fracture criterion and precursor characteristics based on the uniaxial compression AE test of granite. The results obtained were used for monitoring and preventing the occurrence of coal-rock composite dynamic disasters. Li et al. [7, 8] used AE technology in No. 10 Coal Mine of Ping Coal Mine for monitoring and early warning of coal-rock dynamic disaster and proposed AE identification and early warning criteria for coal-rock gas dynamic disaster based on the ringing count and energy value.

In terms of numerical simulation, Tang [9] independently developed RFPA software based on the finite element method (FEM) and conducted a preliminary study on the numerical simulation of AE models. Subsequently, many researchers [10–12] used RFPA to conduct numerical simulations and explore the relationship between AE parameters and rock fracture.

Chaos system is sensitive to initial conditions. In recent years, many researchers have applied chaos theory to the study of coal-rock gas dynamic disasters [13–16], laying the foundational basis for the study of chaos theory in the early warning and prevention of coal-rock gas dynamic disasters.

In this paper, based on the discrete element method (DEM), the numerical simulation method to obtain the AE parameter is used. Based on AE parameter data, the nonlinear chaos theory is introduced for in-depth investigation of the chaotic characteristics of AE parameters and analyzed them. The relationship between the chaotic characteristics of AE parameters and coal-rock fracture was explored to put forward a new precursor criterion of rock fracture, which effectively avoids the error caused by data contingency.

2. PFC Simulation of Coal-Rock Uniaxial Compression Test

PFC is a particle flow numerical simulation software for material damage evolution, fracture mechanism, and deformation process from the mesolevel based on the DEM theory. It is used for simulating the uniaxial compression of coal-rock. It can reproduce the mechanical behavior obtained from field experiments and observe the changes in the whole process from a microscopic view. The generation and development of microcracks in coal-rock will produce an AE phenomenon. In the PFC simulation, each link bond fracture releases strain energy, and an AE signal is generated with each release of strain energy [17]. Therefore, the number of broken particle links is regarded as the number of AE events of coal-rock in this paper. As the elastic modulus of the parallel bond model gradually decreases in the cyclic loading and unloading simulation process, it can simulate the coal-rock damage in the loading process. Therefore, the parallel bond model is selected to simulate coal-rock and calibrate the mesoparameters in this paper [18]. The mesomechanical parameters of the specimen are given in Table 1.

In order to study the AE characteristics during uniaxial compression of coal-rock, the standard specimen with the same size as the laboratory test (50 mm diameter and 100 mm length) was adopted in the simulation, while the displacement loading method with the loading rate of 0.03 m/s was adopted.

3. Uniaxial Compression Test Results and Analysis of Coal-Rock

3.1. Numerical Simulation Characteristics. Figure 1 shows the stress-strain-AE event number variation curve of coal-rock. As can be seen from Figure 1, the curve can be divided into three parts. The first part is the elastic stage of the stress-strain curve. In this stage, there are no AE events at the beginning, but sporadic AE events occur as the loading progresses. The second part is the plastic stage of the stress-strain curve in which the number of AE events increases significantly, and the frequency of AE events accelerates. In the third part, at the postpeak stage of the stress-strain curve, the number of AE events increases sharply to the peak and then decreases sharply until the loading stops.

In Figure 1, the AE event distribution at six points, i.e., a, b, c, d, e, and f, is shown in Figure 2.

In Figure 2, the red parts are the broken particle link keys, namely, the AE events. As can be seen from Figures 2(a) and 2(b), the distribution of AE events in the elastic stage of the stress-strain curve of coal-rock is uniform, random or disordered, and without apparent stress concentration phenomenon. As the loading proceeds, the distribution of AE events appears disordered. However, the events are orderly and begin to show a trend of stress concentration. As shown in Figure 2(c), the AE events may exhibit stress concentration phenomena at 1, 2, 3, and 4, generating large through cracks. After the coal-rock is destroyed, the stress concentration becomes gradually noticeable, particularly in zone 1 and zone 2 in Figures 2(d) and 2(e); the stress concentration phenomenon is the most obvious, followed by zone 3, while in zone 4, it is the weakest. When loading is carried out to point F in Figure 1, as shown in Figure 2(f), only large through cracks in zones 1, 2, and 3 are generated.

3.2. Numerical Calculation Method of Maximum Lyapunov Exponent Based on Small Data Volume Method. The existence of chaos can be determined by the positive and negative properties of the Lyapunov exponent [19]. It is sufficient to look at the largest Lyapunov exponent λ_1 for the chaotic judgment of multidimensional dynamical systems. If $\lambda_1 > 0$, it means there is chaos. The larger the λ_1 value, the more obvious are the chaotic characteristics of the data. If $\lambda_1 = 0$, there is a limit cycle. If $\lambda_1 < 0$, there is a fixed point.

In this paper, the maximum Lyapunov exponent of chaotic time series is calculated using the small data volume method. Specific calculation steps are as follows:

(1) FFT transformation on the time series $\{x(t_i), i = 1, 2, \cdots, N\}$ is performed, and the average period P is calculated

(2) The C-C method is used to calculate the embedding dimension m and time delay τ

(3) Phase space $\{Y_i, i = 1, 2, \cdots, M\}$ is reconstructed based on time delay τ and embedding dimension m

(4) The nearest neighbor point $Y_{j^\wedge}$ of each point Y_j in the phase space is found, and the short separation

Table 1: Mesomechanical parameters of coal-rock specimens.

Minimum particle size (mm)	Grain diameter ratio	Contact modulus E (GPa)	Normal strength of bond σ (MPa)	Tangential strength of bond σ (MPa)	Coefficient of friction
0.3	1.6	0.7	1.105	3	0.8

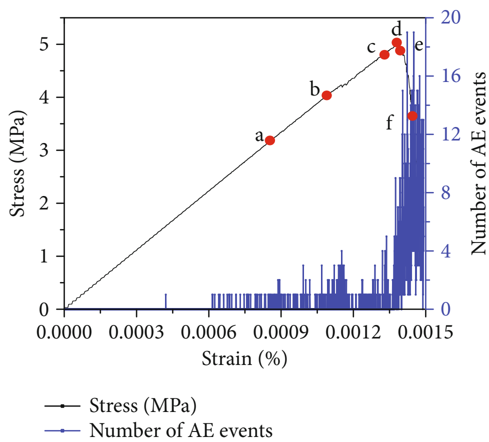

Figure 1: Stress-strain-AE event number variation curve of coal rock.

is limited, i.e.,

$$d_j(0) = \min_{\hat{j}} \left\| Y_j - Y_{\hat{j}} \right\|, \left| j - \hat{j} \right| > P \tag{1}$$

(5) For each point Y_j in the phase space, the distance $d_j(i)$ after i discrete time steps of the adjacent point pair is calculated

$$d_j(i) = \min_{\hat{j}} \left\| Y_{j+1} - Y_{\hat{j}+1} \right\|, \quad i = 1, 2, \cdots, \min\left(M - j, M - \hat{j}\right) \tag{2}$$

(6) The average y_i of all $\ln d_j(i)$ for each $\ln d_j(i)$ is determined:

$$y_i = \frac{1}{q\Delta t} \sum_{i=1}^{q} \ln d_j(i), \tag{3}$$

where q is the number of nonzero $d_j(i)$; $1/\tau \cdot d_j(i) \longrightarrow i$ point curve is drawn, and the regression line is made by the least-squares method; the slope of the line is the maximum Lyapunov exponent λ_1

3.3. Analysis of AE Characteristics Based on Maximum Lyapunov Exponent. During coal-rock uniaxial compression, the distribution of AE events is random. However, although the macrocracks formed in the end are different due to different microscopic parameters, the crack morphology presents a certain regularity, and the distribution process of AE events seems random and irregular. However, in fact, it is orderly, indicating the existence of chaos phenomenon in the process.

In this study, the recorded AE data is divided into groups of every 300 data points. The maximum Lyapunov exponent of each group of data is obtained by using the small-data volume method. The stress-strain-number of AE events-maximum Lyapunov exponent change relation is shown in Figure 3.

It can be seen from Figure 3 that the maximum Lyapunov exponent is greater than zero, indicating that the number of AE events during the coal-rock uniaxial compression has chaotic characteristics. In the elastic stage of the stress-strain curve, when the AE events start occurring, the maximum Lyapunov exponent of each data set cannot be calculated due to the weak continuity of AE events, i.e., there are no chaotic characteristics at this time. With the loading process, the frequency and continuity of AE events increase, and the maximum Lyapunov exponent of some time series can be calculated. The initial value of the maximum Lyapunov exponent fluctuates around zero, and chaos exists, but its characteristics are not prominent. Before the stress-strain curve reaches the peak point, the maximum Lyapunov exponent suddenly increases to the maximum value. At this time, the chaotic characteristics of AE events are the most apparent. In the postpeak stage of the stress-strain curve, the value of the maximum Lyapunov exponent is always smaller than the peak of the maximum Lyapunov exponent before the peak of stress-strain curve and gradually returns to zero, even though the number of AE events increases sharply and reaches the maximum value.

4. Simulation Validation and Analysis

AE is a kind of stress wave phenomenon produced during the deformation or damage of coal-rock under external force. The AE signal can not only reflect the internal structure of the specimens but also further extract the precursor information of the complete damage of the specimen, predict the occurrence of the specimen damage in advance, and then predict the occurrence of the coal-rock power disaster in advance.

If the maximum point of the maximum Lyapunov exponent of the time series of AE events shown in Figure 3 always appears in the stress-strain curve before peak point, then the maximum Lyapunov exponent of maximum points can be applied to warning specimens destroyed. In order to explore this idea, a simulation study on ten groups of coal-rock standard specimens is carried out in this paper. The mechanical

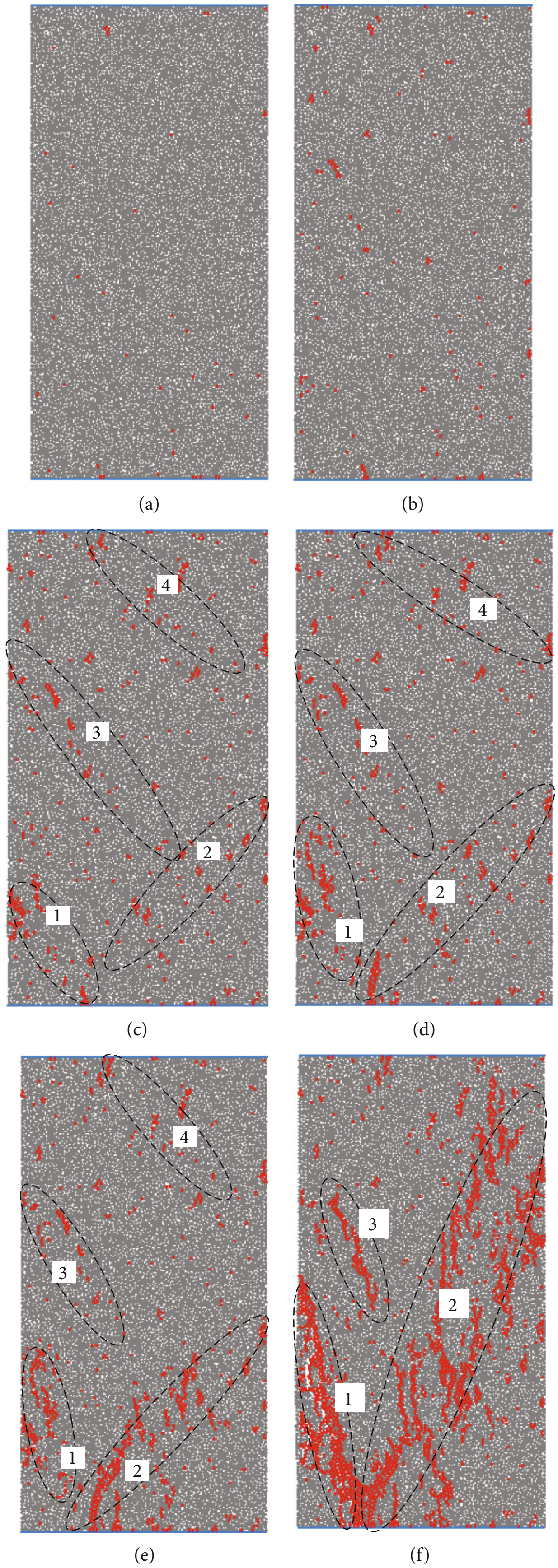

Figure 2: AE event distribution diagram.

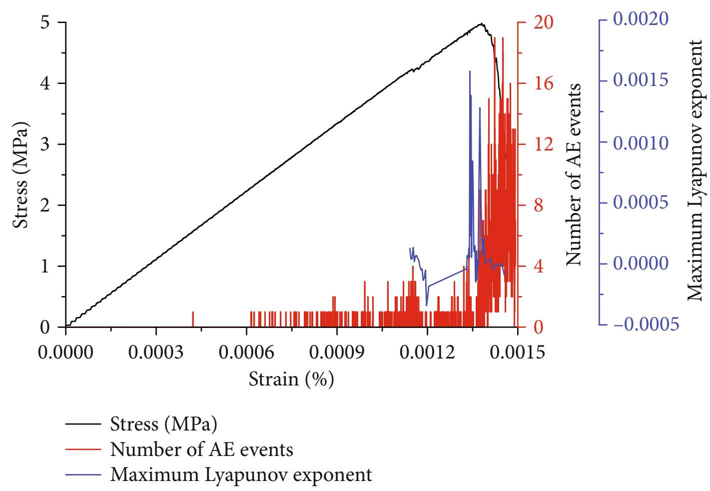

Figure 3: Coal-rock stress-strain-number of AE events-maximum Lyapunov exponential variation diagram.

Table 2: Summary of mechanical parameters of coal-rock standard specimens.

Specimen number	Peak stress (MPa)	Peak strain
1	4.983107832	0.001380257
2	4.25060345	0.001200344
3	2.543909411	0.000707774
4	6.694057265	0.001823883
5	2.976446791	0.00086566
6	8.223110102	0.002464985
7	3.151081825	0.000962933
8	8.619113876	0.002626044
9	3.169886512	0.001005317
10	3.169886512	0.001005317

Table 3: Summary table of maximum Lyapunov exponent.

Specimen serial number	Maximum initial Lyapunov exponent	Maximum Lyapunov exponent submaximum	Maximum Lyapunov exponent maximum
1	5.76×10^{-5}		1.70×10^{-3}
2	1.16×10^{-4}	7.27×10^{-4}	6.20×10^{-3}
3	-3.75×10^{-5}	9.34×10^{-4}	1.70×10^{-3}
4	1.34×10^{-4}		3.53×10^{-4}
5	3.06×10^{-5}		3.70×10^{-3}
6	1.46×10^{-4}	5.82×10^{-4}	1.30×10^{-3}
7	3.06×10^{-5}	5.98×10^{-4}	1.70×10^{-3}
8	1.43×10^{-4}	2.53×10^{-3}	4.28×10^{-3}
9	3.06×10^{-5}	7.66×10^{-4}	1.70×10^{-3}
10	3.06×10^{-5}	7.66×10^{-4}	1.70×10^{-3}

parameters of coal-rock standard specimens are enlisted in Table 2.

Table 3 is the summary table of the maximum Lyapunov exponent. The initial value of the maximum Lyapunov exponent is the first maximum Lyapunov exponent, and the submaximum value of the maximum Lyapunov exponent is the submaximum value before the occurrence of the maximum value of the maximum Lyapunov exponent. It is not the submaximum of all the maximum Lyapunov exponents.

It can be seen from Figures 4–13 that during coal-rock uniaxial compression, the variation pattern of AE events of all specimens is consistent with the scenarios shown in Figure 1, which generally shows a trend of first rising and then declining. In the initial stage of loading, no AE event occurred. As the loading progressed, sporadic AE events started appearing. When the stress-strain curve transitions into the plastic stage, the number of AE events increases significantly, and frequency is accelerated. When the specimen is near failure, the number of AE events increases sharply, and the maximum value appears after the peak point of the stress-strain curve. Subsequently, the number of AE events decreases sharply until the end of loading.

The homogeneity of coal-rock also influences the occurrence time of AE events. The lower the homogeneity of coal-rock, the smaller is the strain corresponding to the initial occurrence of AE events, i.e., the earlier is the initial occurrence time of AE events.

The maximum value of the maximum Lyapunov exponent in the time series of the number of AE events of specimens 1, 2, 3, 5, 7, 8, 9, and 10 appears before the peak of the stress-strain curve, i.e., before the specimen is completely destroyed, the chaotic characteristics of AE event number are the most obvious, which is consistent with the results shown in Figure 3. From Table 3, it can be seen that the maximum value of the largest Lyapunov exponent has a difference in magnitude compared with other values. Among these, there is an order of magnitude difference between specimen 2 and specimen 8, and two orders of magnitude difference between other specimens. However, the

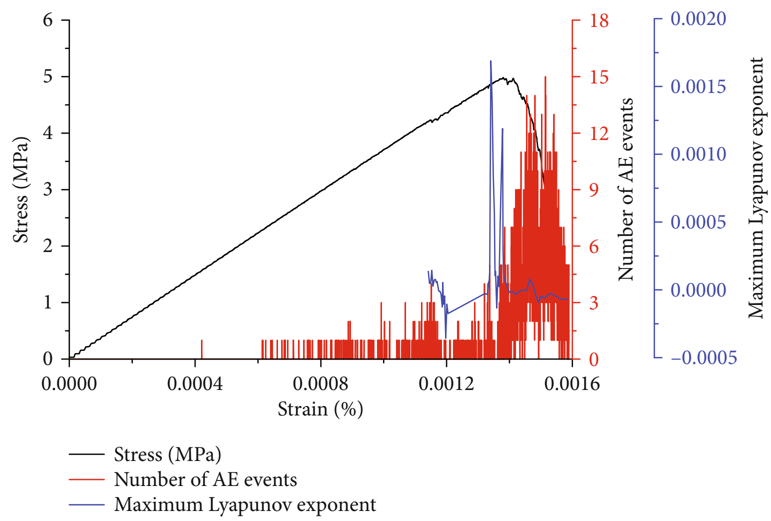

Figure 4: Stress-strain-number of AE events-maximum Lyapunov exponential variation diagram of specimen 1.

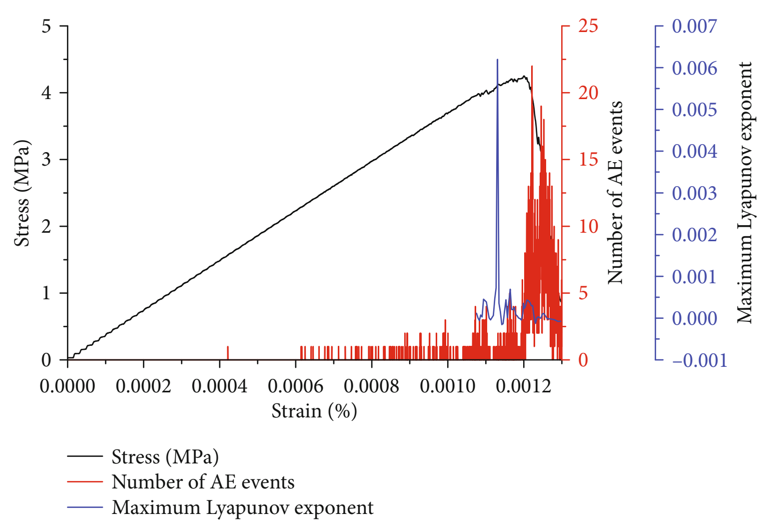

Figure 5: Stress-strain-number of AE events-maximum Lyapunov exponential variation diagram of specimen 2.

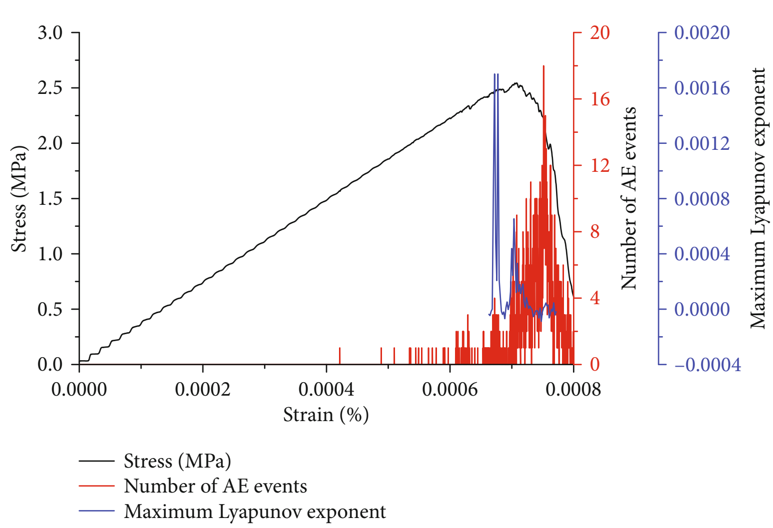

Figure 6: Stress-strain-number of AE events-maximum Lyapunov exponential variation diagram of specimen 3.

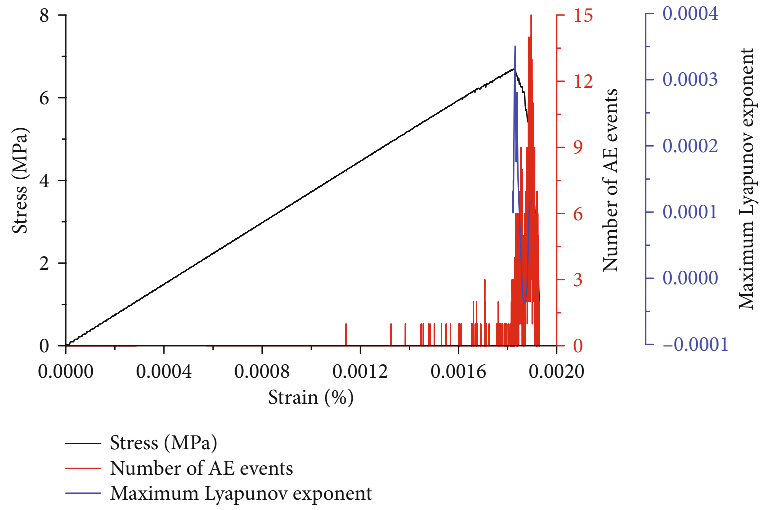

Figure 7: Stress-strain-number of AE events-maximum Lyapunov exponential variation diagram of specimen 4.

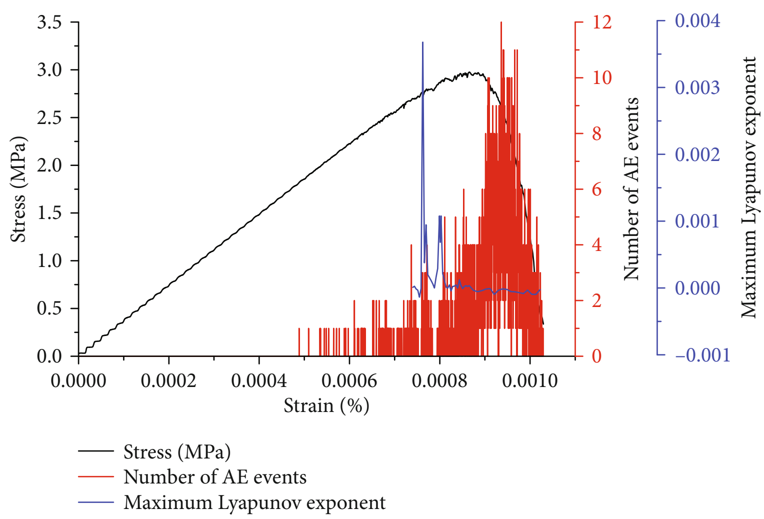

Figure 8: Stress-strain-number of AE events-maximum Lyapunov exponential variation diagram of specimen 5.

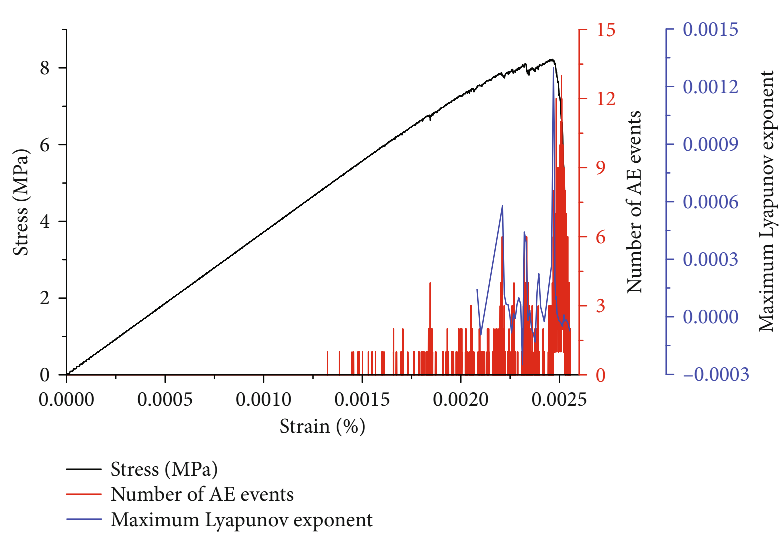

Figure 9: Stress-strain-number of AE events-maximum Lyapunov exponential variation diagram of specimen 6.

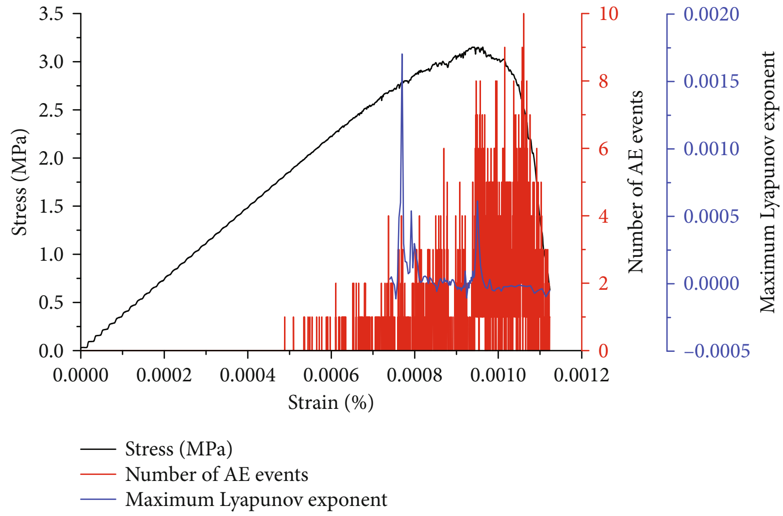

Figure 10: Stress-strain-number of AE events-maximum Lyapunov exponential variation diagram of specimen 7.

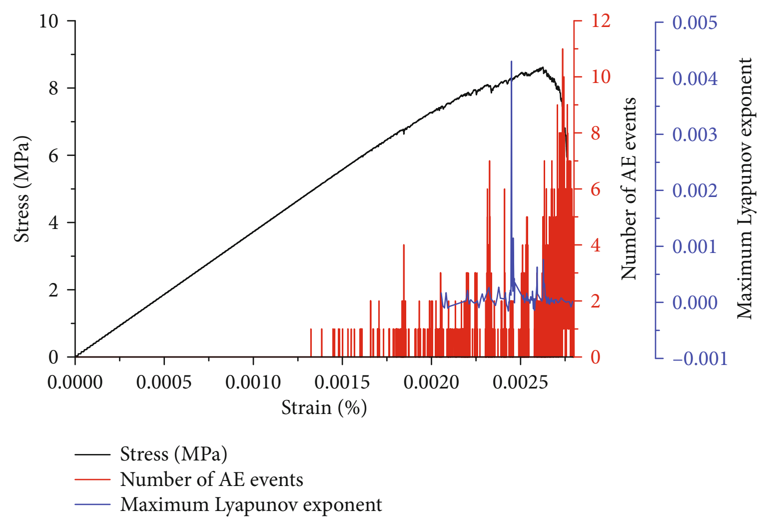

Figure 11: Stress-strain-number of AE events-maximum Lyapunov exponential variation diagram of specimen 8.

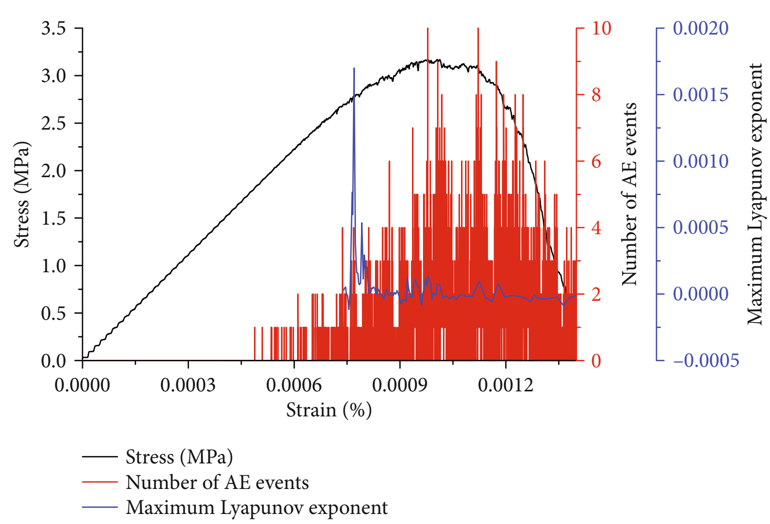

Figure 12: Stress-strain-number of AE events-maximum Lyapunov exponential variation diagram of specimen 9.

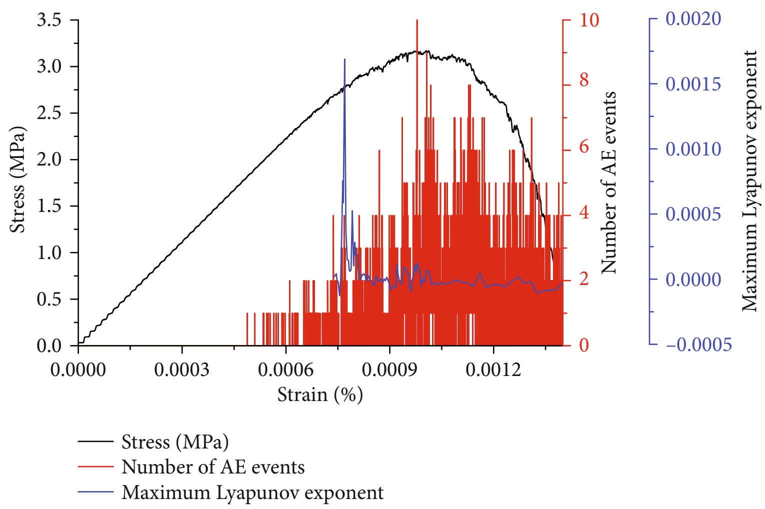

Figure 13: Stress-strain-number of AE events-maximum Lyapunov exponential variation diagram of specimen 10.

maximum value of the maximum Lyapunov exponent remains in the order of 10^{-3}.

In the AE event number time series of specimen 6, the maximum Lyapunov exponent and the peak value of the stress-strain curve appeared almost simultaneously, inconsistent with the results shown in Figure 3. However, it can be seen from Figure 9 that before the maximum point of the maximum Lyapunov exponent appears, there is a submaximum point whose value is greater than 5×10^{-4}.

The maximum Lyapunov exponent of the AE event number time series of specimen 4 appears almost simultaneously with the peak point of the stress-strain curve. However, it could be found that it is located behind the peak of the stress-strain curve, which is inconsistent with the situation shown in Figure 3.

The results of ten sets of simulation tests showed that before the specimens are destroyed, the maximum Lyapunov exponent in the AE event number time series of nine sets of simulation tests suddenly changed to the maximum (the maximum is 10^{-3}) or the submaximum (the submaximum is greater than 5×10^{-4}). This shows that the sudden change of the maximum Lyapunov exponent in AE event number time series can be used as a precursor to rock fracture.

5. Conclusions

In this paper, the relationship between acoustic emission (AE) parameters and coal-rock fracture is investigated by using the discrete element particle flow simulation software PFC. PFC is used to simulate the coal-rock uniaxial compression test for extracting the time series of AE event number, calculate the maximum Lyapunov exponent of the time series, and analyze the chaotic characteristics of AE event number. The following conclusions are drawn by analyzing the stress-strain-AE events-maximum Lyapunov exponent relationship curves of different coal-rocks in uniaxial compression:

(1) During coal-rock uniaxial compression, the variation of AE events generally shows a rising trend, which declines afterward. Before the specimen is near failure, the number of AE events increases sharply, and the corresponding frequency accelerates. The maximum number of AE events occurs after the peak point of the stress-strain curve

(2) The lower the homogeneity of coal-rock specimen, the smaller is the strain corresponding to the initial occurrence of AE events, i.e., the earlier the AE events occur

(3) The maximum Lyapunov exponent of the AE event number time series is high than zero, indicating that the AE event number has chaotic characteristics during coal-rock uniaxial compression

(4) The chaotic characteristics of the number of AE events are most prominent before the specimen is completely destroyed

(5) From the fact that the maximum Lyapunov exponent of the time series of AE events suddenly changes to the maximum (the maximum is of the order 10^{-3}) or the submaximum (the submaximum is greater than 5×10^{-4}) before the specimen is completely destroyed, it is feasible to use the maximum point of the maximum Lyapunov exponent of AE event number time series as the precursor criterion of rock fracture

(6) The maximum Lyapunov exponent of the AE event number time series appears before the maximum AE event number. Compared with the AE identification and warning criterion based on the AE parameters, the precursor criterion based on the chaotic characteristics of the number of AE events can effectively avoid the errors caused by parameter contingency. It can also early forewarn the occurrence of coal-rock damage and improve the accuracy of coal-rock gas dynamic disaster warnings

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

This work is supported by the National Natural Science Foundation (52074167) and the Graduate Education Quality Improvement Project of Shandong Province-Tensor Analysis (SDYKC21064).

References

[1] V. L. Shkuratnik, Y. L. Filimonov, and S. V. Kuchurin, "Experimental investigations into acoustic emission in coal samples under uniaxial loading," *Journal of Mining Science*, vol. 40, no. 5, pp. 458–464, 2004.

[2] B. X. Liu, J. L. Huang, Z. Y. Wang, and L. Liu, "Research on damage evolution and acoustic emission characteristics of coal and rock under uniaxial compression," *Chinese Journal of Rock Mechanics and Engineering*, vol. 28, no. S1, pp. 3234–3238, 2000.

[3] S. G. Cao, Y. B. Liu, and L. Q. Zhang, "Comprehensive analysis of acoustic emission characteristics of coal outburst deformation and failure," *Chinese Journal of Rock Mechanics and Engineering*, vol. S1, pp. 2794–2799, 2007.

[4] Y. B. Zhang, P. Liang, X. X. Liu, L. Shanjun, and B. Z. Tian, "Experimental study on precursors of rock failure based on dominant frequency and entropy of acoustic emission signals," *Chinese Journal of Rock Mechanics and Engineering*, vol. 34, no. S1, pp. 2959–2967, 2015.

[5] A. Q. Li, Q. Zhang, T. Ai et al., "Study on the spatial-temporal evolution behavior of acoustic emission during the whole process of uniaxial compression of granite and its precursors," *Chinese Journal of Geotechnical Engineering*, vol. 38, no. S1, pp. 306–311, 2016.

[6] C. Y. Wang, X. K. Chang, and Y. L. Liu, "Acoustic emission time-frequency domain signal characteristics and precursor identification information during the whole process of granite rupture," *Journal of Yangtze River Scientific Research Institute*, vol. 37, no. 3, pp. 82–89, 2020.

[7] J. J. Zhang, J. G. Li, and T. G. Zhu, "Application of acoustic emission technology in Pingmei no. 10 mine," *Coal Technology*, vol. 36, no. 3, pp. 212–214, 2017.

[8] J. G. Li, "Acoustic emission monitoring and early warning method for gas dynamic disaster of stress-dominated coal-rock in deep mine," *Journal of Shandong University of Science and Technology (Natural Science edition)*, vol. 39, no. 4, pp. 20–27, 2020.

[9] C. A. Tang, "Preliminary study on numerical simulation of rock acoustic emission law," *Chinese Journal of Rock Mechanics and Engineering*, vol. 4, pp. 75–81, 1997.

[10] Y. F. Fu and C. A. Tang, "Numerical simulation and experimental study on Kaiser effect of rock acoustic emission," *Mechanics and practice*, vol. 6, pp. 42–44, 2000.

[11] Y. Q. Rui and C. A. Tang, "Numerical simulation of rock fracture sliding process and its acoustic emission," *Journal of Engineering Geology*, vol. 4, pp. 357–361, 2001.

[12] T. Xu, C. A. Tang, Y. B. Zhang, and L. Yuan, "Parallel numerical simulation of peeling failure process of FRP concrete interface," *Journal of solid mechanics*, vol. 32, no. 1, pp. 88–94, 2011.

[13] H. H. Liu, "Application of chaos theory to prediction of coal mine gas concentration," *Shanxi Electronic Technology*, vol. 4, pp. 43-44, 2011.

[14] L. N. Shi, "Coal and gas outburst prediction research method based on chaos theory," *Computer Knowledge and Technology*, vol. 9, no. 28, 2013.

[15] L. Su, *Study on prediction of gas emission based on chaotic time series, [M.S. thesis]*, University of Science and Technology, Xi an, China, 2012.

[16] B. Wang and J. J. Han, "Chaotic time series prediction method of gas emission in a mine," *Modern Mining*, vol. 34, no. 8, pp. 206-207, 2018.

[17] Y. F. Wang, Z. J. Huang, and F. Cui, "Micromechanical damage evolution mechanism of coal rock failure process," *Journal of China Coal Society*, vol. 39, no. 12, pp. 2390–2396, 2014.

[18] Y. C. Yin, T. B. Zhao, Y. L. Tan, and F. H. Yu, "Reconstruction and numerical experiment of rock meso-model based on Otsu image processing," *Rock and Soil Mechanics*, vol. 36, no. 9, pp. 2532–2540, 2015.

[19] J. H. Lv, L. A. Lu, and S. H. Chen, *Chaos Time Series Analysis and Its Application*, Wuhan University Press, Wuhan, China, 2002.