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Cluster and information entropy analysis of acoustic emission during rock failure process

Zhenghu Zhang[1a], Lihua Hu*[1], Tiexin Liu[2b], Hongchun Zheng[3c] and Chun'an Tang[1d]

[1]State Key Laboratory of the Coastal and Offshore Engineering, School of Civil Engineering,
Dalian University of Technology, No.2 Linggong Road, Ganjingzi District, Dalian City, Liaoning Province 116024, China
[2]Department of Civil Engineering, Dalian Maritime University, 1 Linghai Road, Dalian City, Liaoning Province 116026, China
[3]China Three Gorges Corporation, 1 Yuyuantan South Road, Haidian District, Beijing 100038, China

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Abstract. This study provided a new research perspective for processing and analyzing AE data to evaluate rock failure. Cluster method and information entropy theory were introduced to investigate temporal and spatial correlation of acoustic emission (AE) events during the rock failure process. Laboratory experiments of granite subjected to compression were carried out, accompanied by real-time acoustic emission monitoring. The cumulative length and dip angle curves of single links were fitted by different distribution models and distribution functions of link length and directionality were determined. Spatial scale and directionality of AE event distribution, which are characterized by two parameters, i.e., spatial correlation length and spatial correlation directionality, were studied with the normalized applied stress. The entropies of link length and link directionality were also discussed. The results show that the distribution of accumulative link length and directionality obeys Weibull distribution. Spatial correlation length shows an upward trend preceding rock failure, while there are no remarkable upward or downward trends in spatial correlation directionality. There are obvious downward trends in entropies of link length and directionality. This research could enrich mathematical methods for processing AE data and facilitate the early-warning of rock failure-related geological disasters.

Keywords: cluster method; information entropy; acoustic emission (AE); rock; failure

1. Introduction

The stability of surrounding rock mass is vital in tunnel excavation, coal mining, hydropower engineering, etc. In contrast, rock damage and instability may lead to various geological hazards, such as rockburst, collapse, landslide and large deformation of tunnel. These geological hazards not only severely threaten the security and service life of engineering works, but also endanger the lives of employees. Rock is a typical heterogeneous and anisotropic material. The damage evolution process of rock is complicated and unpredictable compared to other engineering materials, such as concrete or cement mortar. Rock failure is attributed to crack initiation, propagation and coalescence subjected to external loads from a microscopic perspective (Zhang and Deng 2020). Therefore, the damage evolution process of rock subjected to external loads, especially temporal and spatial correlations of microscopic cracks, is of great significance to understand and forecast rock failure-related geological disasters.

Generally, quantitative investigation of rock damage, particularly microscopic cracks, is difficult to realize. Acoustic emission (AE) is produced by microscopic cracks in a material due to a rapid release of localized strain energy when the material is subjected to external loads (Karser 1950, Aggelis 2011, Elbatanouny *et al.* 2014, Kim *et al.* 2019). As a powerful non-destructive testing (NDT) approach, AE technique has been widely used to evaluate the real-time formation and growth of micro cracks in rock mechanics and engineering (Ohnaka and Mogi 1982, Read *et al.* 1995, Přikryl *et al.* 2003, Kim *et al.* 2015, Chen and Irfan 2018). The significant growth in the number and release rate of AE counts or events can be viewed as a precursor to rock instability (Shiotani *et al.* 2001, Cheon *et al.* 2011). Many scholars investigated temporal and spatial distribution of acoustic emission events during the damage evolution process of rock, and these studies mainly focus on the variation of location and quantity of AE signals (e.g., Lei *et al.* 2004, Li *et al.* 2010, Rodríguez and Celestino 2019). The distribution of AE activity is disordered to a certain extent, which makes it difficult to evaluate the damage evolution process of rock directly. Therefore, it is essential to adopt some quantitative statistics of AE activity. The change of seismic b-value, which characterizes the

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*Corresponding author, Ph.D.
E-mail: hulihuaxs@dlut.edu.cn
[a]Ph.D.
E-mail: zhenghuzhang@dlut.edu.cn
[b]Ph.D.
E-mail: txliu@dlmu.edu.cn
[c]Ph.D.
E-mail: zhenghongchun@foxmail.com
[d]Professor
E-mail: tca@mail.neu.edu.cn

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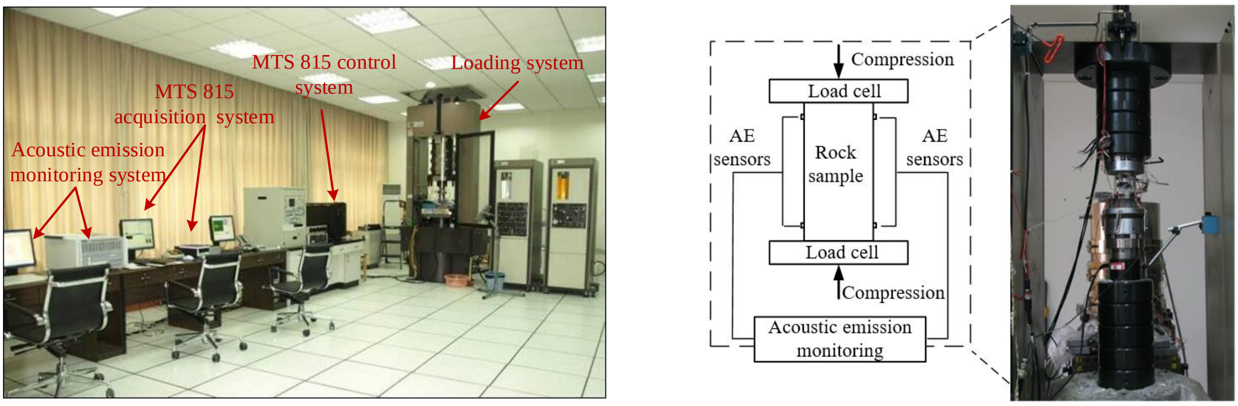

(a) Rock mechanics testing system and acoustic emission monitoring system

(b) AE sensor layout and test photo

Fig. 1 Schematic diagram of laboratory experimental setup

(a) Before test

(b) After test

Fig. 2 Typical granite sample

frequency-magnitude relation of micro cracks, were introduced to assess the damage degree of rock (Scholtz 1968, Lei *et al.* 2004). It was found that the distribution of AE events during the failure process of rock shows fractal characteristics, and the fractal property was also investigated (Hirata *et al.* 1987, Kong *et al.* 2017). The variation of spatial correlation length was also applied to represent the critical point characteristics preceding the catastrophic failure of rock (Li *et al.* 2010, Zhang *et al.* 2017). However, there are few studies on statistical analysis of temporal and spatial correlation between microscopic cracks, especially correlation dimension and directionality. Moreover, it is important to compare the differences between correlation dimension and directionality of micro cracks when the rock is subjected to external load.

The objective of this research is to assess the damage evolution process of brittle rocks, particularly temporal and spatial correlation of microscopic cracks based on the single-link cluster method and information entropy theory. Laboratory experiments of brittle rock subjected to compression were carried out. Real-time AE monitoring was performed during the entire rock failure process. The single-link cluster method and information entropy theory were introduced to statistically analyze the spatial and temporal correlation between micro failures which are symbolized by AE signals. The distribution functions of link length and directionality were determined. The spatial correlation length and spatial correlation directionality were calculated with the increasing normalized applied stress. The entropies of link length and link directionality were also discussed. Finally, the validity of clustering method and information entropy theory to study the damage evolution of brittle rocks was revealed.

2. Experimental setup

The overall experimental setup is shown in Fig. 1. Experiments were conducted on an MTS815 Flex Test GT Rock Mechanics Testing System. The PCI-2 acoustic emission monitoring system, made by American Physical Acoustics Corporation, was used to automatically monitor AE signals over the loading process. AE signals were detected and collected by eight Micro30 sensors for the accurate location of AE events. The sensors were distributed on the surface of each cylindrical specimen symmetrically with respect to the longitudinal axis, which is conducive to the collection of AE signals. The sampling rate was set as 1 MHz. The pre-amplification was set as 40 dB according to the background noise level. Acoustic emission monitoring begins simultaneously when the load is applied to the rock sample. The AE monitoring system has a good sensitivity to AE signals. Vaseline was used between each rock specimen and AE sensors to ensure good sensor coupling.

Granite was used in the present study. The four cylindrical specimens with an approximate diameter of 50 mm and an approximate height of 100 mm were prepared to conduct uniaxial compression tests, as shown in Fig. 2.

3. Experimental results and analysis

3.1 Characteristics of AE signals produced during the rock failure process

A typical axial stress- axial strain curve during the uniaxial compression test is shown in Fig. 3. Physical and mechanical properties of rock were calculated. The density of granite is 2.62 × 10^3 kg/m^3, and the average uniaxial compression strength is 76.55 MPa.

To investigate spatial and temporal distributions of AE signals during the rock failure process, location results of AE events of granite specimens were analyzed. The typical spatial distributions of AE events with the increasing stress level are shown in Fig. 4. The release rate of AE events shows a gradual upward trend during the whole loading process. There are few AE events produced by rock specimens at the initial stage of loading. The closure of pre-existing microcracks and dislocation of microstructure result in the appearance of a small number of AE events. More and more AE events are produced with the increase in stress, which can be attributed to new crack initiation, propagation and coalescence. At the end of the loading process, especially near the peak strength, AE events increase significantly. The generation and coalescence of macro failure plane lead to the final failure of rock specimens. Generally, the accumulative process of AE events agrees well with the failure process of rock.

3.2 Statistical analysis of spatial and temporal distributions of link lengths

3.2.1 Statistical analysis of link length distribution based on clustering method

Clustering analysis is a common data analysis method to find the internal structure of data. Clustering is the process of classifying data objects, so that the objects in the same cluster have a high degree of similarity with each other, while the objects belonging to different clusters are irrelevant (Gordon 1999, Jain *et al.* 1999, Xu and Wunusch 2005, Ferreira *et al.* 2016). The common clustering algorithms contain hierarchical method, partitioning method, density-based method, Grid-based method and model-based method. When the research objects are points in space, distance is generally used to measure their similarity. The smaller the distance, the higher the similarity. Single-link (also named nearest-neighbour) clustering is a widely-used approach to analyze spatial clustering characteristics of point data (Frohlich and Davis 1990, Zhang *et al.* 2017). In this paper, single-link clustering method is used to analyze the spatial and temporal distributions of AE events, which can be viewed as three dimensional points in space.

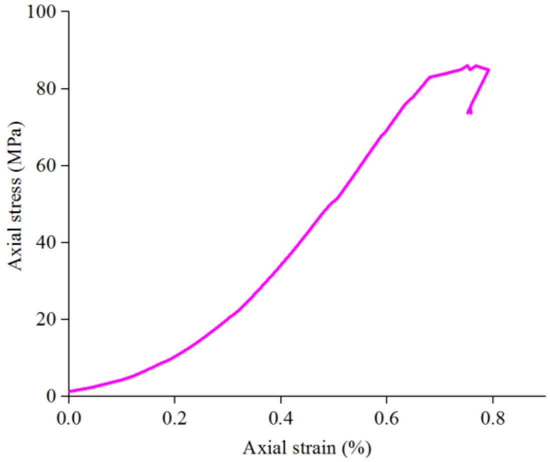

Fig. 3 Typical axial stress- axial strain curve during uniaxial loading of rock

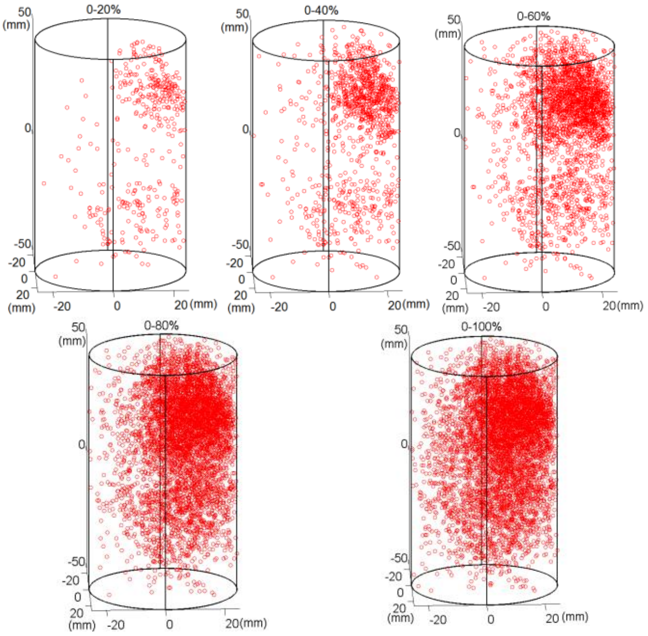

Fig. 4 Typical spatial distribution of AE events with the increasing stress level

For a certain AE event sequence with the quantity of N, an $N \times N$ matrix D is defined and each element in the matrix represents the spatiotemporal distance between a pair of AE events. Specifically, the element d_{mn} of the m^{th} row and the n^{th} column represents the temporal-spatial distance between the m^{th} and n^{th} AE events.

$$d_{mn} = \sqrt{(x_m - x_n)^2 + (y_m - y_n)^2 + (z_m - z_n)^2 + B(t_m - t_n)^2} \quad (1)$$

where d_{mn} refers to the spatiotemporal distance between the two AE events; x, y and z symbolize the three dimensional Cartesian coordinates of the location of an AE event; t and B are the occurrence time and spatiotemporal correlation coefficient, respectively.

Assuming that $B=0$, the element d_{mn} represents the spatial distance between two events. To search for the nearest neighbor of the i^{th} event, comparisons among every

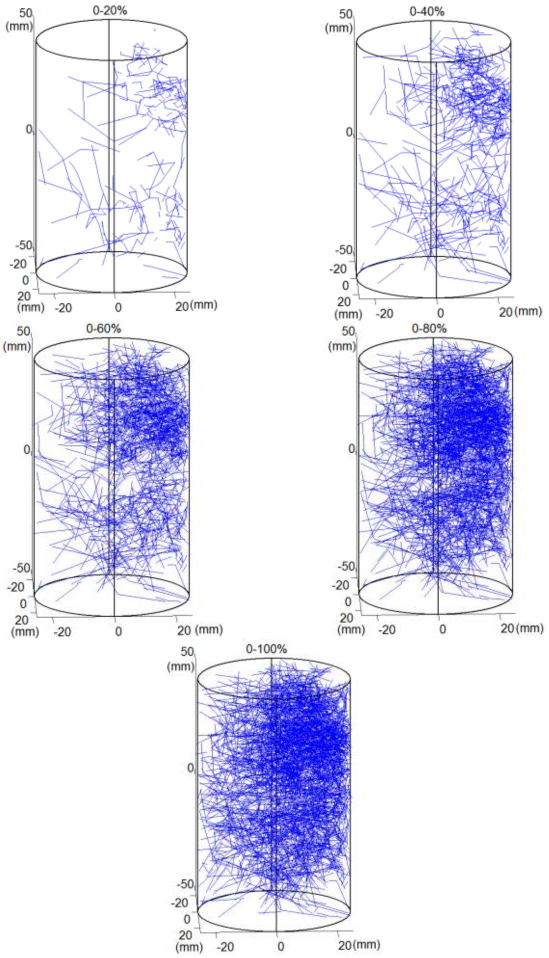

Fig. 5 Single-link cluster structure of AE events with the increasing stress level

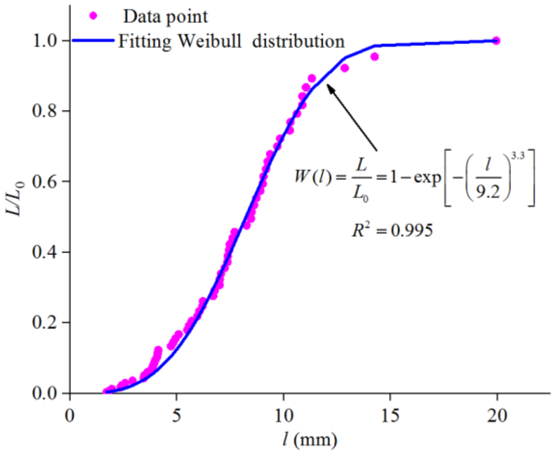

Fig. 6 Typical relationship and fit function between the relative accumulative link length L/L₀ and link length l

element of the i^{th} row are made. When the element d_{ij} is the least, the j^{th} event is the nearest neighbor of the i^{th} event. The linear connection between the i^{th} and j^{th} events is called a single link. After all the events are searched, the single link subsets are established. The total of subsets is less than $N/2$.

A new matrix E is built by using these subsets. The element e_{pq} of the p^{th} row and the q^{th} column in the matrix E corresponds to the spatial distance between the p^{th} and q^{th} subsets, as presented in Eq. (2).

$$e_{pq} = d_{st} = \min(d_{mn}), (m, s \in p, n, t \in q) \quad (2)$$

Suppose that the q^{th} subset is the nearest to the p^{th} subset, the linear connection between the s^{th} and t^{th} events is the single link between the p^{th} and q^{th} subset. Consequently, the single link clustering structure is established.

Based on the abovementioned single-link clustering method, clustering analysis of AE events released during the rock damage evolution process was made. The moving window method was applied and the window length was set as 100. The clustering of AE events at different normalized applied stress on rock specimens is shown in Fig. 5. The blue solid lines refer to single links between events and red dotted lines are single links between subsets. Note that since the red lines are few and dotted, they are not obvious when the image is small. Obviously, the clustering results can directly reflect the damage evolution process of rock. The clustering of AE events corresponds well to macro crack propagation.

To further discuss the statistical feature of clustering, the characteristics of single link were statistically analyzed. The lengths of every single links were calculated by Eq. (1) and the proportions distributed in different link length intervals were counted. The symbol L is defined as the cumulative length of single links whose lengths are less than l. The symbol L_0 refers to the cumulative length of all the single links. Thus, the ratio of L/L_0 represents the normalized accumulative link length. A typical relationship and best fit function between the normalized accumulative link length L/L_0 and link length l are shown in Fig. 6. By comparing the goodness of fit of common models, including linear, exponential, power law, normal distribution and Weibull distribution, it can be found that the coefficients of determination (R^2) for Weibull distribution were highest (greater than 0.95) among these models. Therefore, the distribution of accumulative link length obeys Weibull distribution and can be expressed as:

$$W(l) = \frac{L}{L_0} = 1 - \exp\left[-\left(\frac{l}{\beta}\right)^{\alpha}\right] \quad (3)$$

where α and β refer to distribution parameters, which can be determined by a goodness of fit test.

The cumulative distribution function $W(l)$ in Eq. (3) refers to the probability that a link length is smaller than l. Zöller *et al.* (2001) studied the critical point concept for earthquakes and defined the spatial correlation length λ as the link length l where the probability density function is equal to 0.5. The definition of the spatial correlation length λ was also adopted in this paper to reflect the spatial scale of AE event distribution. Specifically, a series of spatial correlation lengths with the normalized applied stress were calculated by the condition $W(l)$=0.5.

Fig. 7 shows typical change trend of spatial correlation length with the increasing normalized applied stress. The normalized applied stress is defined as the ratio of the

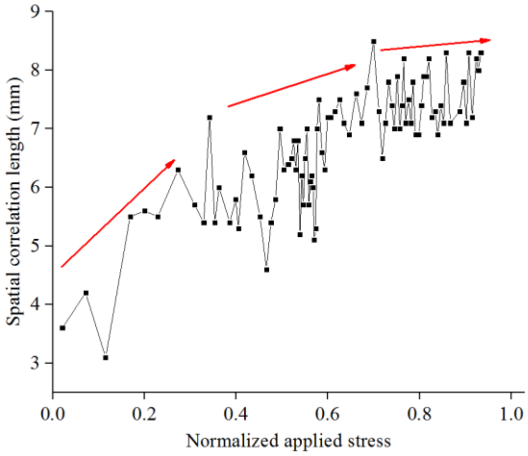

Fig. 7 Spatial correlation length of AE events with the normalized applied stress

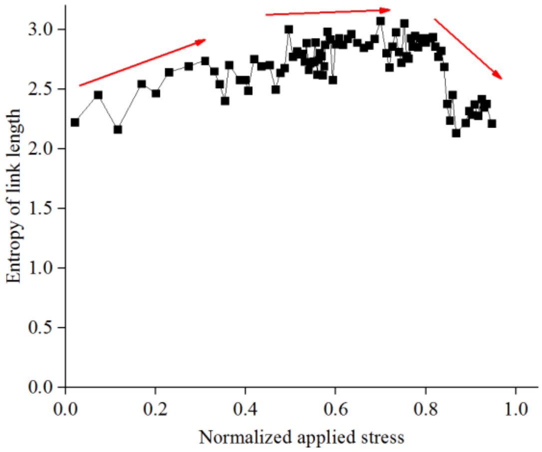

Fig. 8 Entropies of link length distribution with the normalized applied stress

current stress level to the uniaxial compression strength. At the initial loading stage, the spatial correlation length is small. With the growth of the applied stress on the rock specimen, the spatial correlation length increases gradually.

3.2.2 Statistical analysis of link length distribution based on information entropy method

Entropy is one of the parameters that characterize the state of matter in thermodynamics. Its physical meaning is a measure of the degree of chaos in the system. The more chaotic a system is, the greater its entropy; the more orderly it is, the smaller its entropy. Shannon (1948) introduced the concept of entropy into information and communication field. The proposal of information entropy is to solve the problem of quantitative measurement of information. The information entropy $H(x)$ of the random variable x can be determined by:

$$H(x)=E[I(x_i)]=E[\log(2,1/P(x_i))],(i=1,2,...n) \tag{4}$$

where the symbols E, I and P refer to the mathematical expectation, amount of information and probability function.

When the number of samples is finite, the formula for entropy can be expressed as:

$$H(x)=-\sum_{i=1}^{n}P(x_i)\ln(P(x_i)) \tag{5}$$

$$\sum_{i=1}^{n}P(x_i)=1,(i=1,2,...,n) \tag{6}$$

$$P(x_i)=\frac{N_i}{N_0} \tag{7}$$

where N_0 is the sum of single links; N_i refers to the number of single links distributed in the range $[j\Delta l,(j+1)\Delta l]$, ($j$=1,2,…,$m$); Δl is the spacing and m is taken as the integer portion of the ratio of the maximum link strength $l_{\max}$ and the spacing Δl.

Through Eqs. (5)-(7), a series of entropies were determined with the loading time. Fig. 8 shows the change trend of entropies of link lengths with the normalized applied stress. It can be found that the entropy of link length shows an upward trend at the initial stage of loading. Subsequently, there are small fluctuations in the entropy-normalized applied stress curves at the medium stress level. The entropy of link length declines remarkably prior to rock failure.

3.3 Statistical analysis of spatial and temporal distributions of link directionality

3.3.1 Statistical analysis of link directionality distribution based on clustering method

As described in Section 3.2, if the j^{th} event is the nearest neighbor of the i^{th} event, the linear connection between the i^{th} and j^{th} events can be viewed as a single link. A single link points from an event (i^{th}) to its nearest neighbor (j^{th}) event. Every single link can be considered as a spatial vector. Therefore, the single link vector $\vec{A}$ can be expressed as:

$$\vec{A}=(A_x,A_y,A_z)=(x_j-x_i,y_j-y_i,z_j-z_i) \tag{8}$$

where A_x, A_y, A_z symbolize the components of the spatial vector ($\vec{A}$) in the x, y, z directions; x, y and z are the Cartesian coordinates of AE event, respectively.

The statistical characteristics of single link lengths have been investigated in Section 3.2. This section focuses on the directionality of single links. Thus, the unit vector $\vec{a}$ corresponding to every spatial vector were calculated:

$$\vec{a}=\frac{\vec{A}}{|\vec{A}|}=(a_x,a_y,a_z) \tag{9}$$

where a_x, a_y, a_z symbolize the components of the unit vector $\vec{a}$ in the x, y, z directions, respectively.

The starting point of each unit vector is shifted to the origin $O(0,0,0)$ and thus the coordinates of the terminal point M are equal to the coordinates of corresponding unit vector. Since rock specimens in this paper are cylindrical,

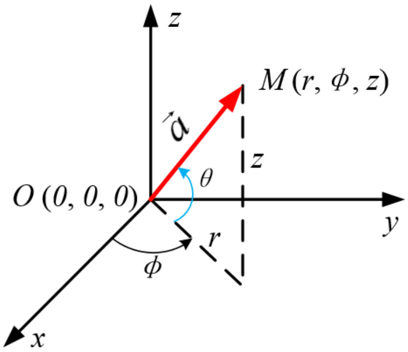

Fig. 9 The coordinates of the unit vector of single link

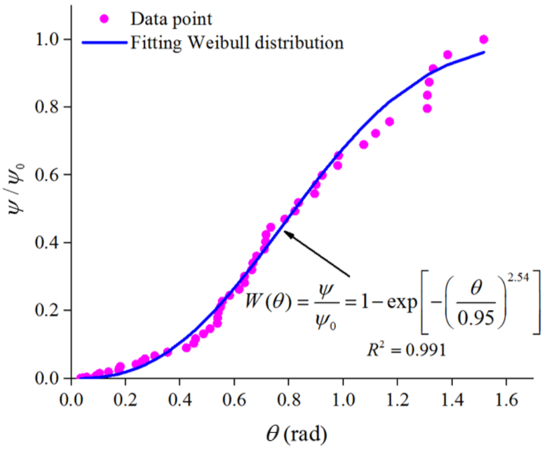

Fig. 10 Typical relationship and fit function between the relative accumulative dip angle (ψ/ψ_0) and dip angle θ

the rectangular coordinates of unit vector were converted into the cylindrical coordinates:

$$r=\sqrt{a_x^2+a_y^2}\ ;\ \phi=\arctan(\frac{a_y}{a_x})\ ;\ z=a_z \tag{10}$$

New micro cracks align in the loading direction when rock specimen is subjected to external load (Brace *et al.* 1966, Diederichs *et al.* 2004, Morgan *et al.* 2013). The loading direction in this study is along *z* axis. Therefore, the dip angle θ, which is the angle between the unit vector and the projection of the unit vector in the xy plane, can be applied to characterize the directionality of single links, as shown in Fig. 9. At this time, the range of the dip angle is from $-\frac{\pi}{2}$ to $\frac{\pi}{2}$, i.e., $\theta\in[-\frac{\pi}{2},\frac{\pi}{2}]$. Because the propagation and interaction of microcracks are usually symmetrical, the range of θ should satisfy the condition $\theta\in[0,\frac{\pi}{2}]$. Thus, the dip angle θ can be calculated by:

$$\theta=\arctan(\frac{|z|}{r})=\arctan(\frac{|a_z|}{\sqrt{a_x^2+a_y^2}}) \tag{11}$$

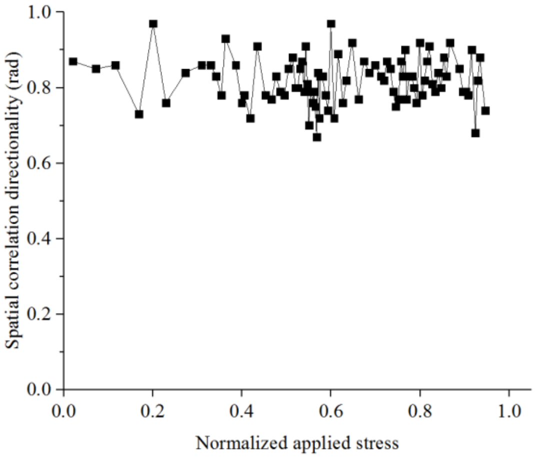

Fig. 11 Spatial correlation directionality of AE events with the normalized applied stress

To investigate the statistical characteristics of link directionality, the dip angle θ were statistically analyzed. The directionalities of every single links were determined by Eq. (11). The percentages of the dip angles distributed in different angle interval were calculated. The symbol ψ is defined as the cumulative angle sum of single links whose dip angles are below θ. The symbol ψ_0 represents the cumulative sum of all the single links. Consequently, the ratio (ψ/ψ_0) refers to the normalized accumulative dip angle. Typical relationship between the normalized accumulative dip angle (ψ/ψ_0) and the dip angle θ is shown in Fig. 10. After conducting the goodness of fit tests, the distribution of accumulative dip angles also obeys a Weibull distribution. The distribution fit function can be expressed as:

$$W(\theta)=\frac{\psi}{\psi_0}=1-\exp\left[-\left(\frac{\theta}{\eta}\right)^{\gamma}\right] \tag{12}$$

The cumulative distribution function $W(\theta)$ in Eq. (12) refers to the probability that the dip angle of a single link is less than θ. In this study, a new concept called the spatial correlation directionality (ξ) was defined to symbolize the spatial directionality of AE event distribution. Similarly to the definition of the spatial correlation length, the spatial correlation directionality (ξ) is determined as the dip angle θ where the probability density function is equal to 0.5. This is, a series of spatial correlation directionalities with the normalized applied stress were calculated by the condition $W(\theta)=0.5$.

Typical variation of spatial correlation directionality versus the normalized applied stress is shown in Fig. 11. There are fluctuations in the spatial correlation directionality during the whole loading process. It can be observed that there are no remarkable upward or downward trends with the increasing stress.

3.3.2 Statistical analysis of link directionality distribution based on information entropy method

As described in Section 3.2.2, entropies of link directionality can be calculated by Eqs. (5)-(7). The only difference between this Section and Section 3.2.2 is that N_i in Eq. (7) refers to the number of single links distributed in the interval $[j\Delta\theta,(j+1)\Delta\theta]$, $(j=1,2,...,m)$; $\Delta\theta$ is the angle spacing and m is taken as the integer portion of the ratio of the maximum dip angle $\theta_{\max}$ and the spacing $\Delta\theta$.

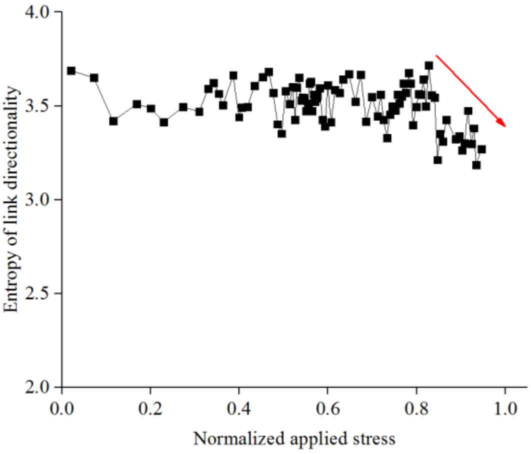

Fig. 12 Entropies of link directionality distribution with the normalized applied stress

The change trend of entropy of link directionalities with the increasing normalized applied stress is shown in Fig. 12. The entropy of link length decreases slightly with the increment of stress at the initial stage of loading. Subsequently, the entropy of link directionality show relatively stable change with small fluctuations at the medium stress level. Finally, the entropy of link directionality declines significantly when the stress ratio exceeds 80%. It indicates that there is an obvious decrease in the entropy of link directionality prior to rock failure.

4. Discussion

Clustering method and information entropy theory were introduced in this study to investigate the temporal and spatial correlation of AE event distribution in rock. The applicability of clustering analysis and entropy theory was discussed. This research provides a new perspective for understanding on the evolution process of rock failure and facilitates the early-warning of rock failure-related geological disasters. Moreover, the findings in this paper could be helpful in enriching mathematical methods for processing and analyzing AE data to evaluate rock failure, and hence to better solve rock failure-related problems in civil engineering.

From statistical analysis results of link length distribution based on cluster method, it can be found that the spatial correlation length grows gradually with the increase of the applied stress on the rock specimen. This observation is coincident with the past research in earthquakes (Frohlich and Davis 1990, Zöller *et al.* 2001, Tyupkin and Giovambattista 2005). Micro crack initiation, propagation and coalescence lead to the formation of macro failure surfaces in rock subjected to external load, which finally results in rock failure. The reason for the growth of the spatial correlation length is that cracks transform from small-scale to large-scale with the increasing stress level.

To symbolize the spatial directionality of AE event distribution, a new concept named the spatial correlation directionality was defined and determined as the dip angle θ where the probability density function is equal to 0.5. The definition of the spatial correlation directionality is similar to that of the spatial correlation length. Through statistical analysis, there are no remarkable upward or downward trends with the stress level. This indicates there is no significant change in the micro crack propagation direction with the increasing stress. Micro crack propagation direction is mainly dependent on the local stress concentration, which is closely related to micro structure, the distribution of preexisting microdefects, mineral composition of rock.

Through statistical analyses of entropy of link length and directionality, the entropies decline significantly prior to rock failure. This indicates there is an obvious decrease in the entropy in terms of both scale and direction. Micro crack distribution is increasingly orderly at a high stress level, especially prior to rock macro failure, which is the reason for the change of entropies. The change of entropy reflects the degree of chaos in micro crack distribution. The decrease of entropies of link length and directionality indicate the more orderly distribution in micro cracks prior to rock final failure.

This research is based on the uniaxial compression tests of granite specimens at the laboratory scale. It is worth to further investigate this correlation under other loading conditions, e.g., tension, shear and at a large field test scale.

5. Conclusions

To investigate spatial and temporal correlations of AE event distribution in rock subjected to compression, clustering method and information entropy theory were introduced. Spatial and temporal distributions of link length and directionality during the rock failure process were statistically analyzed. The conclusions of this study are as follows:

(1) After performing goodness of fit tests, the coefficients of determination (R^2) for Weibull distribution are greater than 0.95. Therefore, the distributions of accumulative link length and directionality obey Weibull distribution.

(2) Spatial correlation length was adopted to symbolize the spatial distribution of AE events. The spatial correlation length increases gradually with the growth of the applied stress on the rock specimen.

(3) A new concept called the spatial correlation directionality was defined to symbolize the spatial directionality of AE event distribution. There are fluctuations in the spatial correlation directionality during the whole loading process. There are no remarkable upward or downward trends with the stress level.

(4) Through statistical analyses of entropy of link length and directionality, it is found that the entropies decrease significantly prior to rock failure. This can be attributed to the fact that the micro crack distribution is more orderly prior to rock macro failure.

Acknowledgments

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