

Progressive fracture evolution and mechanical response of cavity-containing sandstone under low-frequency disturbance

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Abstract: During deep coal mining, interlayer rock strata subjected to high static stress and low-frequency dynamic load are prone to fracture and instability, often leading to dynamic disasters. To investigate the dynamic response of rock fracture, deformation, and mechanical behavior under low-frequency disturbances, uniaxial compression tests were conducted on perforated sandstone specimens at different loading rates. This study explores the crack evolution, fracture ejection patterns, and dynamic strain behavior of sandstone under disturbance. The results reveal the following key findings: (1) The mechanical properties of sandstone are significantly influenced by the loading rate, with peak strength increasing nonlinearly as the loading rate rises. When the loading rate increases fivefold, the average peak strengths of the single-hole, double-hole, and triple-hole specimens increase by 9.67%, 14.64%, and 9.44%, respectively. However, as the number of perforations increases, the overall load-bearing capacity of sandstone decreases, and the average peak strengths are reduced by 12.58%, 12.15%, and 13.23%, respectively. (2) The acoustic emission (AE) characteristics and stress-time evolution curves of sandstone exhibit distinct inflection points. AE activity is relatively weak during the crack initiation stage, but AE events increase sharply before failure, accompanied by an exponential rise in AE energy. This phenomenon can serve as an early warning indicator of dynamic failure in high-stress sandstone under low-frequency disturbances. (3) Based on the failure modes and the extent of surface spalling and block ejection, sandstone failure can be classified into three types. The mean σ_x/σ_z values for type I, II, and III specimens are 0.959, 0.765, and 0.687, respectively, indicating significant differences in mechanical properties among different failure modes. (4) The strain distribution in the rock specimens is closely related to the number of perforations. As the number of perforations increases, pronounced stress shielding zones and horizontal tensile strain zones develop between the holes during loading, providing the main pathways for crack propagation.

Keywords: low-frequency disturbance; loading rate; crack propagation; fracture ejection; strain behavior

1 Introduction

In 2024, China's coal production reached 4.76 billion tons, marking a 1.3% year-on-year increase, indicating sustained demand for coal^[1]. As high-quality coal resources near the surface become increasingly scarce, coal mining operations are progressively extending deeper into the strata. This shift has led to more frequent simultaneous operations on upper and lower working faces during excavation. Influenced by multiple prior mining activities, the stress field environment and the properties of coal-rock media undergo significant changes during upward mining in excavation roadways^[2–4]. Under the combined effects of high-stress conditions and long-range excavation-induced disturbances, the rock mass becomes highly

susceptible to dynamic disasters such as roof collapse, spalling, and rock bursts. The interplay between remote disturbances and abnormal mining-induced pressure variations results in anomalous mechanical behavior and catastrophic failure of the surrounding rock. Conventional on-site mining experience and classical rock mechanics theories are increasingly revealing their limitations in addressing such disasters^[5–8]. As shown in Fig. 1, when coal extraction occurs above an excavation roadway, the interlayer rock between them serves as the primary load-bearing structure, subjected to both long-range excavation-induced stress waves and the overlying rock load. Simultaneously, the excavation roadway below the mining seam falls within the range of advanced support pressure while also being affected by mining disturbances,

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forming a typical “high-stress and low-frequency disturbance” coupled loading condition. Dynamic disturbances are a crucial trigger for high-stress rock instability, interacting with cumulative rock damage to establish a significant roadway failure mode.

In rock mechanics studies, disturbance and damage are often closely related^[9–10]. Under high-frequency disturbances, damage progresses rapidly. Under low-frequency disturbances, the rock undergoes a relatively slow damage process, but as the number of disturbances increases, the microcracks in the material expand rapidly in a shorter period of time, thus affecting the overall stability^[11–13]. For example, long-distance blasting operations, fault slip, and mining machinery vibration all have relatively obvious low-frequency disturbance states.

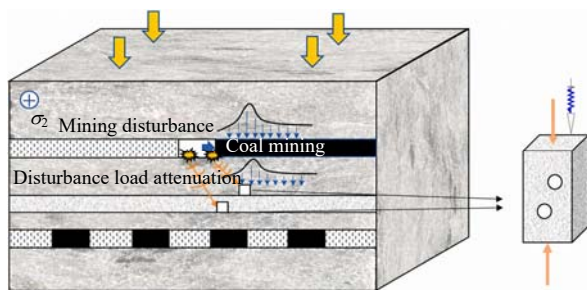


Fig. 1 Schematic diagram of the stress mode of overlying mining stratum

In recent years, extensive research has been conducted on the dynamic characteristics of rocks under disturbance conditions. Regarding the mechanical behavior of rocks under low-frequency disturbance loading, researchers have conducted a series of mechanical tests using true triaxial testing machines^[14], conventional triaxial testing machines^[15], and uniaxial compression testing machines^[16]. Li et al.^[17–18] investigated the instability and failure characteristics of deep rock masses under mining-induced disturbances through combined static-dynamic loading experiments. Jiang et al.^[19] characterized rock damage and crack propagation under different disturbance amplitudes and frequencies using a true triaxial testing machine, discovering that as disturbance frequency increased, the crack area of the rock exhibited a growth trend. The interlayer excavation roadway can be considered analogous to cavities within rock specimens. Both Chinese and international scholars have studied the damage and failure patterns of rocks containing cavities. Bai et al.^[20] used numerical simulation software to model the fracture process of rock specimens with cavities, concluding that the failure mode of porous specimens follows a splitting failure pattern, with fractures approximately parallel to the loading direction. Dai et al.^[21] conducted dynamic impact tests on standard rock specimens with axial boreholes and found that as impact loading increased, the cumulative

rock damage exhibited a power-law relationship with strain rate. Although previous studies have extensively explored static-dynamic loading and rock damage characteristics in porous rocks, the mechanical response of porous rocks under low-frequency disturbances and varying loading rates remains insufficiently explored, and the multi-field coupling mechanisms are not yet well understood.

Utilizing a dynamically and statically coupled testing apparatus developed by the China Coal Research Institute, this study conducted uniaxial compression experiments on sandstone specimens with different cavities under low-frequency disturbance conditions. Acoustic emission (AE) monitoring and VIC-3D non-contact full-field strain measurement systems were employed to monitor the entire rock fracture process in real time. The study primarily investigates the mechanical properties of porous sandstone under low-frequency disturbance and different loading rates, analyzing its strength degradation, strain evolution, and energy variation. Based on acoustic emission parameters and VIC-3D monitoring results, this study clarifies the progressive damage process of porous sandstone and reveals the intrinsic correlation between nonlinear dynamic responses and progressive damage under low-frequency disturbance conditions. The findings provide critical theoretical and practical insights into understanding the instability and failure mechanisms of deep coal-rock masses and the scientific prevention and control of deep coal-rock dynamic disasters.

2 Test equipment and scheme

2.1 Sample preparation

The rock samples used in the experiment were collected from the 15024 working face of a mine in Shandong province. Following the guidelines provided by the International Society for Rock Mechanics and Rock Engineering (ISRM)^[22], the intact rock blocks retrieved from the site were processed in the laboratory through coring, cutting, and polishing. The samples were then prepared into standard rectangular specimens with dimensions of 50 mm in length, 50 mm in width, and 100 mm in height, ensuring that the non-parallelism of the end faces was less than 0.02 mm. The cavity diameter of each sample is 5 mm. For single-cavity samples, the cavity is located at the center of the sample; for double-cavity samples, the cavities are located at one-third of the sample's diagonal; and for triple-cavity samples, the cavities are located at one-quarter of the sample's diagonal. The equivalent strength of the rock decreases nonlinearly with changes in the number or arrangement of cavities, especially when the cavities are nearly through-hole. Diagonal arrangements can form “potential fracture chains” that can be used to analyze this critical evolution process (see Fig. 2).



Fig. 2 Standard sandstone samples with cavities

The processed rock samples are grayish-white, with a uniform and fine texture, and are free from macro cracks and bedding. The samples were weighed and subjected to ultrasonic sound velocity testing to eliminate those with significant deviations in density and sound velocity. These processed rock samples accurately represent the in-situ properties of fine sandstone formations in coal mine rock strata, including density, strength, porosity, and microstructures such as mineral particles, pores, and microcracks. The physical and mechanical properties of the sandstone used are presented in Table 1.

Table 1 Physical and mechanical properties of rocks and test scheme

Serial number	Amplitude /MPa	Frequency /Hz	Density /($\text{kg} \cdot \text{m}^{-3}$)	Wave speed /($\text{m} \cdot \text{s}^{-1}$)	Elastic modulus /GPa	Number of cavities	Loading rate /($\text{mm} \cdot \text{min}^{-1}$)	Uniaxial compressive strength /MPa
A-1	16	1	2 543.13	3 867.22	7.53	1	0.1	77.59
A-2			2 557.63	3 859.16	8.31	1	0.5	85.58
A-3			2 546.52	3 798.36	8.88	1	2.5	93.32
B-1			2 499.36	3 789.56	5.91	2	0.1	60.85
B-2			2 564.32	3 795.28	6.53	2	0.5	67.24
B-3			2 551.95	3 745.69	7.61	2	2.5	79.86
C-1			2 498.56	3 645.94	5.70	3	0.1	58.67
C-2			2 524.57	3 685.42	6.34	3	0.5	65.32
C-3			2 546.89	3 678.55	6.69	3	2.5	70.25

2.2 Experimental equipment

The experiments were conducted using the WDW-100E microcomputer-controlled dynamic-static coupled testing machine developed by the China Coal Research Institute. This testing machine has a maximum axial load capacity of 1 000 kN and supports displacement loading rates ranging from 0.001 to 300 mm/s. To enable real-time monitoring of surface strain, crack propagation, and fracture behavior during testing, all rock specimens were pretreated with speckle spraying before loading. During the experiment, a VIC-3D non-contact full-field strain measurement system, a static high-definition camera, and a high-speed camera were employed for synchronized monitoring. These systems captured critical parameters such as surface strain and rock fragment ejection velocity, with the cameras operating at a resolution of $2\,448 \times 2\,048$ pixels and a strain resolution of 10×10^{-6} . Throughout the deformation process, a PAC-II AE monitoring system was used to detect AE signals corresponding to internal microfractures within the rock samples. The AE monitoring methodology followed the approach of Qian et al.^[23], with seven AE sensors evenly distributed on the back and sides of the rock specimens. The PCI-II monitoring system was configured with a preamplifier gain of 40 dB, a threshold of 40 dB, and a sampling frequency of 25 kHz. AE monitoring was synchronized with the mechanical testing of the sandstone specimens. The experimental setup and monitoring system configuration are shown in Fig. 3.

2.3 Experimental plan

This study focuses on analyzing the failure characteristics of rocks under the coupled effects of low-frequency disturbance, different cavity conditions, and varying loading rates. To achieve this, preliminary tests were first conducted in three groups using conventional static uniaxial compression tests to determine appropriate pre-static loading levels and low-frequency disturbance load parameters. The pre-tests applied loading rates of 0.1, 0.5, and 2.5 mm/min until rock failure, obtaining the uniaxial compressive strength (UCS) of the rock. Different loading rates significantly affect the failure mode and energy dissipation process of rocks. At a low loading rate of 0.1 mm/min, rock failure exhibits a multi-stage, localized collapse pattern, resulting in a typical post-peak, multi-peak stress-strain response, reflecting the gradual and complex nature of the failure process. At higher loading rates (0.5 and 2.5 mm/min), the rock structure suddenly loses stability, manifested by a sharp drop in stress, a post-peak “missing” characteristic, corresponding to a typical brittle failure process. The results, as shown in Fig. 4, served as the basis for determining the initial disturbance conditions and amplitude in subsequent experiments. In engineering practice, the complex stress waves acting on surrounding rock can be decomposed into harmonic waves of different frequencies via Fourier transform^[24]. Additionally, existing studies on rock mechanics under low-frequency disturbance commonly adopt harmonic waves as the input disturbance

load for simplification^[25]. Therefore, this study employed sinusoidal stress waves with specified amplitudes and frequencies as the low-frequency disturbance load. According

to the experimental results of Xi et al.^[26], the damage effect of disturbance loading on rock materials intensifies with increasing frequency.

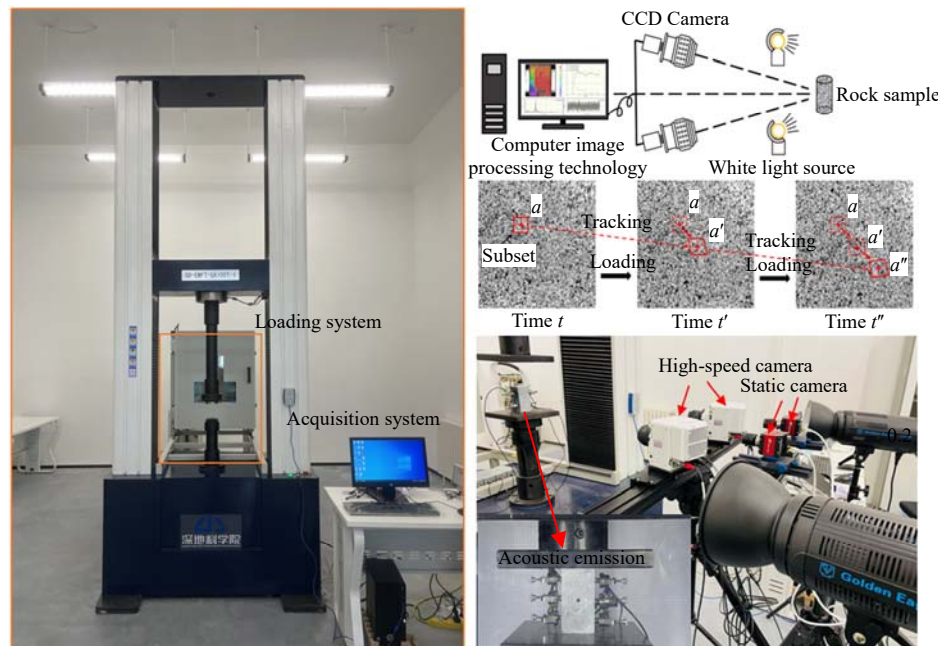


Fig. 3 Loading system and monitoring system

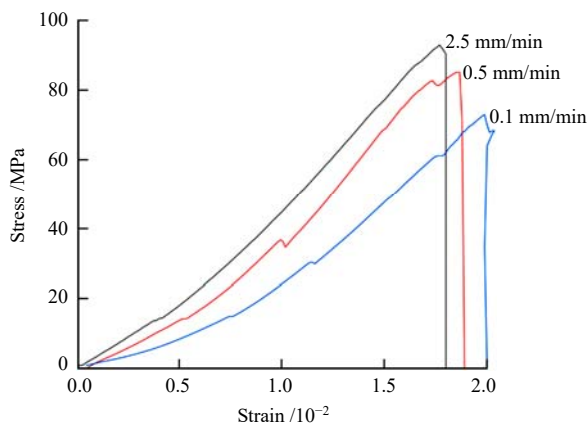


Fig. 4 Uniaxial compressive strength of rock

This study primarily investigates the influence of disturbance load amplitude under low-frequency conditions. Considering stress wave attenuation and underground in-situ measurements (1–10 Hz), the disturbance load frequency was set to 1 Hz. To achieve a high-stress state, the pre-static load level was set at the transition point where crack propagation shifts from stable to unstable. The disturbance initiation point was set at 80% of the UCS, with a disturbance amplitude of 16 MPa. The corresponding experimental scheme is presented in Table 1.

The entire experimental process was divided into

two stages: the static loading stage and the dynamic disturbance stage. Initially, based on different experimental schemes, loading was applied at rates of 0.1, 0.5, and 2.5 mm/min until reaching 80% of the UCS. At this point, the load was held constant, and low-frequency disturbance was subsequently applied, with a disturbance cycle consisting of 1 000 repetitions. If the rock sample failed during the disturbance cycles, the disturbance was stopped immediately. If the rock sample remained intact after 1 000 cycles, loading was resumed at the initial rate until the specimen failed. This process allowed for the determination of the rock's damage strength under disturbance conditions and quantified the impact of low-frequency disturbances on the mechanical properties of the specimens.

3 Dynamic information evolution of acoustic emission

3.1 Analysis of acoustic emission waveform characteristics

Figure 5 presents the multi-channel continuous AE waveforms, clearly illustrating that a significant number of AE signals were generated throughout the fracturing process. The AE waveforms across different channels show a high degree of consistency in terms of signal quantity and energy characteristics. During the loading process, when rock failure occurred, all channels recorded a substantial number of high-energy AE signals. Although certain channels (e.g., Channel 7) exhibited lower

overall AE amplitudes, this can be attributed to their installation positions. Nevertheless, the signal variation trends remained consistent with those of other channels. Specifically, during the main fracture stage, all channels detected high-energy signals. When other channels recorded intense AE signals, Channel 7 also captured corresponding signals, albeit with lower overall energy—sometimes too low to be detected. As a result, during the localization process, the signals from such channels were excluded due to their insufficient energy levels.

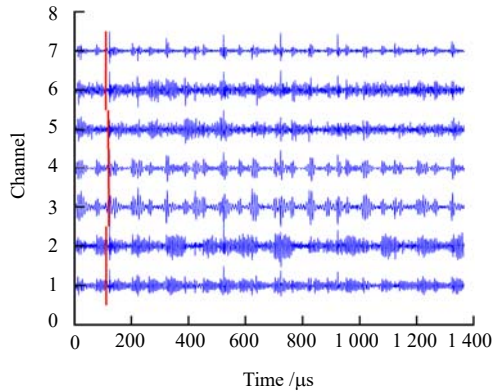


Fig. 5 Continuous acoustic emission waveform of multi-channel monitoring

3.2 Acoustic emission parameter characteristics at different loading rates

In this study, the autoregressive model and Akaike's information criterion (AIC) are employed to identify the signal arrival time^[27], and the simplex method is used to calculate the location of acoustic emission events^[28]. Based on acoustic emission localization, the AE focal mechanism is further analyzed using moment tensor theory. The moment tensor analysis method relies on Green's function. For the signal monitored by acoustic emission technology, the initial amplitude $A(x)$ of the signal can be expressed by Eq. (1)^[29].

$$A(x) = \frac{C_s \text{Ref}(t, r)}{R} (r_1 r_2 r_3) \times \begin{pmatrix} m_{11} & m_{12} & m_{13} \\ m_{12} & m_{22} & m_{23} \\ m_{13} & m_{23} & m_{33} \end{pmatrix} \begin{pmatrix} r_1 \\ r_2 \\ r_3 \end{pmatrix} \quad (1)$$

where R represents the distance between the crack initiation location (y) and the sensor (x); r_1 , r_2 , r_3 are the directional cosines from the crack location to the sensor; $\text{Ref}(t, r)$ denotes the reflection coefficient at the sensor location. When the signal arrives perpendicularly at the rock surface, $\text{Ref}(t, r)$ reaches its maximum value. C_s is a coefficient related to sensor sensitivity, which can be calibrated using the lead break test. Once C_s and $\text{Ref}(t, r)$ are determined, the moment tensor components of the acoustic emission (AE) source can be calculated using Eq. (1). The moment tensor $\mathbf{M}$ is a third-order symmetric tensor containing six independent components,

and therefore, at least six effective signals are required for moment tensor calculation. The failure type of microcracks is determined by analyzing the eigenvalues of the moment tensor $\mathbf{M}$.

AE count and AE energy are commonly used AE characteristic parameters. The AE count directly reflects the damage state of the rock material, while AE energy reveals the formation, propagation, and evolution of new microcracks. The AE characteristic parameters and stress-time evolution curves for different loading rates and numbers of cavities in the rock are shown in Fig. 6. For single-cavity rock, under loading rates of 0.1 and 0.5 mm/min, the AE count increases slowly before the disturbance stops and then rises sharply during the later loading stages. The disturbance stop point serves as the inflection point for this acceleration. At a loading rate of 2.5 mm/min, the stable propagation of microcracks is disrupted during the disturbance stage, leading to a rapid increase in AE count before the disturbance ceases. The AE energy density at this rate is slightly higher than under the other two loading conditions. In the early and middle stages of loading, AE energy remains at a low level for all three loading rates. However, as stress increases in the later stages, dynamic failure occurs, causing a sharp rise in AE energy at the moment of failure. For double-cavity rock, the AE count and AE energy trends under 0.1 and 0.5 mm/min loading rates are similar to those observed in single-cavity rock. However, at a loading rate of 2.5 mm/min, the AE count exhibits a wave-like increasing trend, reaching approximately twice the count observed at lower loading rates, with a total of 886 AE events recorded. For triple-cavity rock, the overall stress level is significantly lower than that of single-cavity and double-cavity rocks. Under a loading rate of 2.5 mm/min, the rock fails after only 102 disturbance cycles, indicating that multi-cavity rock is more prone to failure under high loading rates. At a loading rate of 0.1 mm/min, the AE count exhibits two acceleration phases, corresponding to the disturbance initiation and termination points. Under loading rates of 0.5 mm/min and 2.5 mm/min, the AE count increases steadily until failure. AE energy decreases as the loading rate increases, with the failure energy at 0.1 mm/min being approximately three times that at 0.5 mm/min and about six times that at 2.5 mm/min.

3.3 Variation of mechanical parameters

The elastic modulus of different rock specimens was calculated, and the scatter plot and mean variation of uniaxial compressive strength (σ_c) and elastic modulus (E) for various failure types were plotted, as shown in Fig. 7. According to Fig. 7(a), the elastic modulus E increases with the loading rate v . At $v = 0.1$, 0.5, and 2.5 mm/min, the average values of E are 5.97, 7.27, and 7.67 GPa, respectively. Compared with $v = 0.1$ mm/min, the elastic modulus increases by 24.8% and 28.5%, respectively. However, as the number of cavities increases,

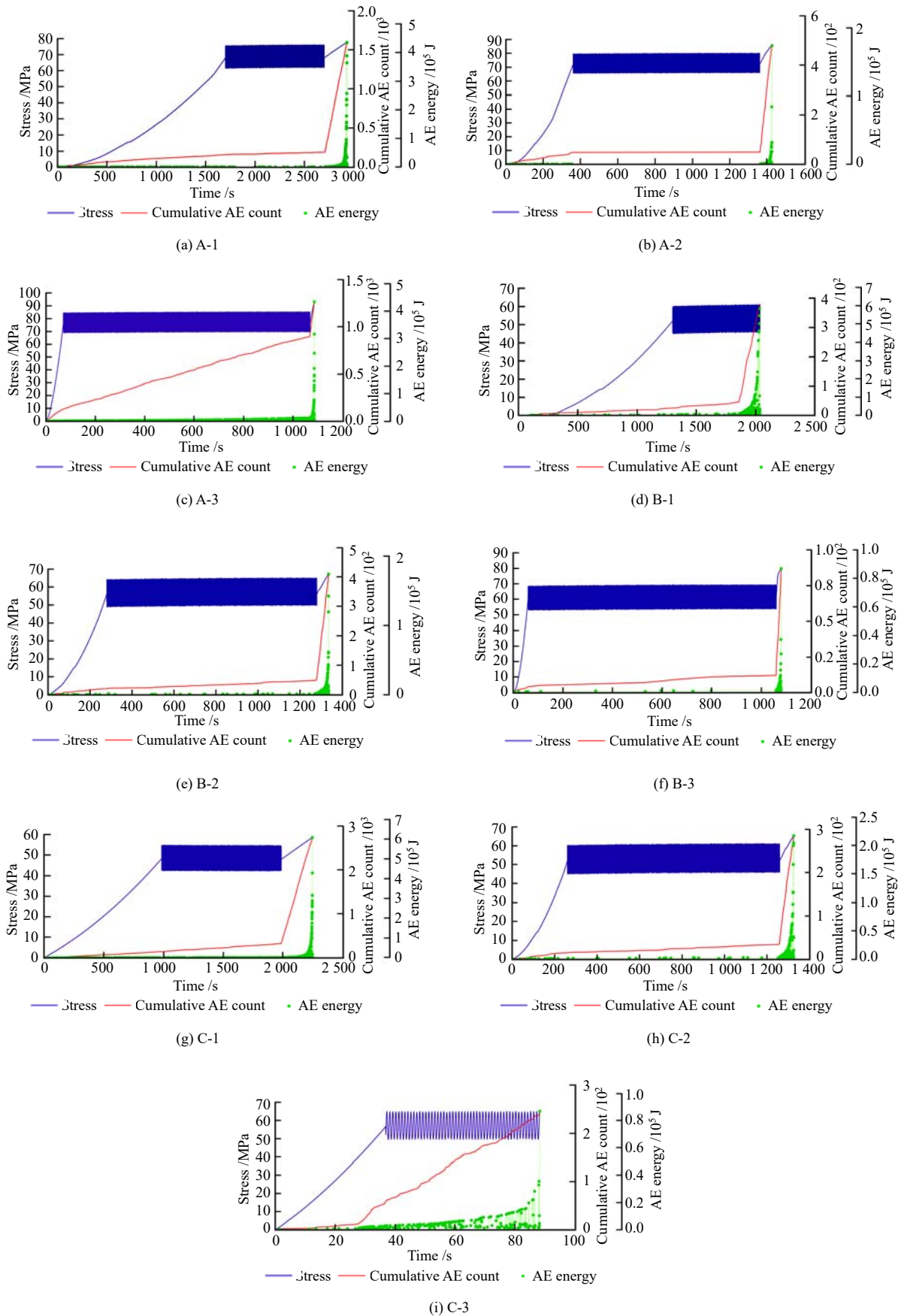


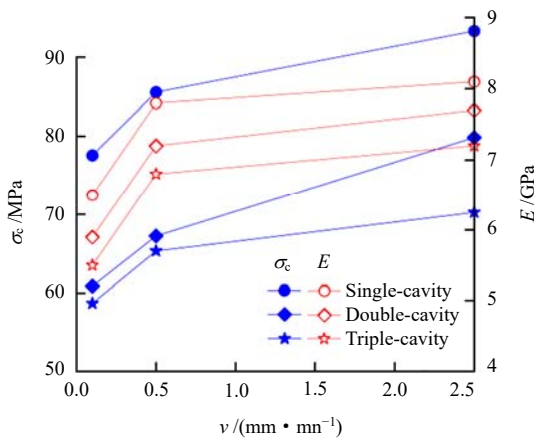
Fig. 6 AE characteristic parameters and stress-time evolution curves of rock samples under different schemes

the elastic modulus E decreases. The average E values for single-cavity, double-cavity, and triple-cavity rocks are 7.47, 6.93, and 6.5 GPa, respectively, representing

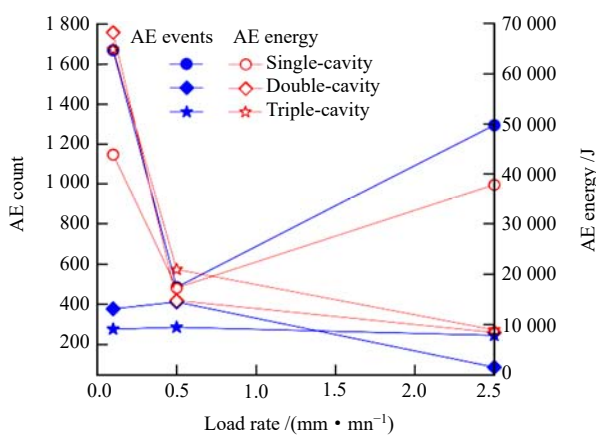
reductions of 7.2% and 12.9% compared to single-cavity rock. As shown in Fig. 7(a), the average σ_c values at $v = 0.1, 0.5$, and 2.5 mm/min are 65.70, 72.67, and 81.14 MPa,

respectively. σ_c exhibits a rapid initial increase followed by a slower rise with increasing v , with the highest σ_c occurring at $v = 0.1$ mm/min. Additionally, σ_c decreases with an increasing number of cavities. The average σ_c values for single-cavity, double-cavity, and triple-cavity rocks are 85.49, 69.31, and 64.75 MPa, respectively, indicating reductions of 18.93% and 24.26% compared to single-cavity rock.

Figure 7(b) shows that the AE count of rock specimens exhibits no clear trend with changing loading rate. For single-cavity rock, the AE count initially decreases and then increases with increasing loading rate, reaching its lowest value of 486 at $v = 0.5$ mm/min. For double-cavity rock, AE energy is significantly lower than that of single-cavity rock and follows a trend of initially increasing and then decreasing with increasing loading rate, with a peak AE count of 413 at $v = 0.5$ mm/min. Meanwhile, the AE energy of triple-cavity rock remains relatively stable, showing no significant fluctuations with increasing loading rate. The AE energy of rock specimens decreases rapidly at first and then declines more gradually with increasing loading rate. For single-cavity rock, AE energy initially decreases and then increases with increasing loading rate.



(a) Variation of uniaxial compressive strength and elastic modulus



(b) Variations in AE events and AE energy

Fig. 7 Changes in rock characteristic parameters with loading rate

3.4 Evolution of disturbance source and failure mechanisms

The classification of source mechanisms in AE is typically based on moment tensor (MT) analysis, which is used to describe the stress state of microfractures within rocks. In three-dimensional source mechanism classification plots, the source mechanisms are categorized using percentage components such as DC (double couple), CLVD (compensated linear vector dipole), and ISO (isotropic), presented in a three-dimensional coordinate system. DC indicates a double-couple mechanism, where data points concentrated along the DC axis suggest that the fracture is primarily shear-dominated. CLVD refers to a linear vector dipole, and when data points are concentrated along the CLVD axis, it indicates the presence of complex, asymmetric shear fractures. ISO represents isotropic failure, with points concentrated along the ISO axis signifying significant volumetric strain, where the rock is more likely to experience spalling.

As shown in Fig. 8, the three-dimensional classification of source mechanisms reveals that AE events are unevenly distributed, predominantly concentrated in the bottom region and becoming progressively sparse with increasing depth. The color scale at the bottom of the image reflects the severity of different AE events. At lower loading rates, green events dominate, indicating that events in the later stages of loading are more prominent, while high-energy events (depicted as red points) are less frequent. Early loading primarily shows microfractures with high CLVD and ISO components, but just before final failure, DC components may increase, suggesting a transition to shear-dominated failure. In contrast, at higher loading rates, red and blue events dominate, indicating more significant events in the later stages of loading. Additionally, as the number of cavities increases, early loading shows a predominance of DC and ISO components, signifying that fractures develop in a shear-dominated manner, accompanied by high-pressure dilation. This distribution pattern suggests significant spatial heterogeneity in the internal stress state of the rock mass, with distinct temporal and spatial evolution of the fracture events. High-density AE events likely correspond to the initiation and early propagation of microcracks within the rock mass, while low-density regions may reflect the stable propagation of large-scale fractures or the attenuation phase following local stress release.

4 VIC-3D test and microscopic analysis

In order to analyze the relationship between local rock fracture and ejection under different loading rates, the strain cloud diagrams of the rock surface with different cavity conditions were extracted through VIC-3D monitoring. By analyzing the changes in data at different monitoring points, the influence of loading rate and holes on local rock fracture and ejection was clarified. The monitoring point layout is shown in Fig. 9.

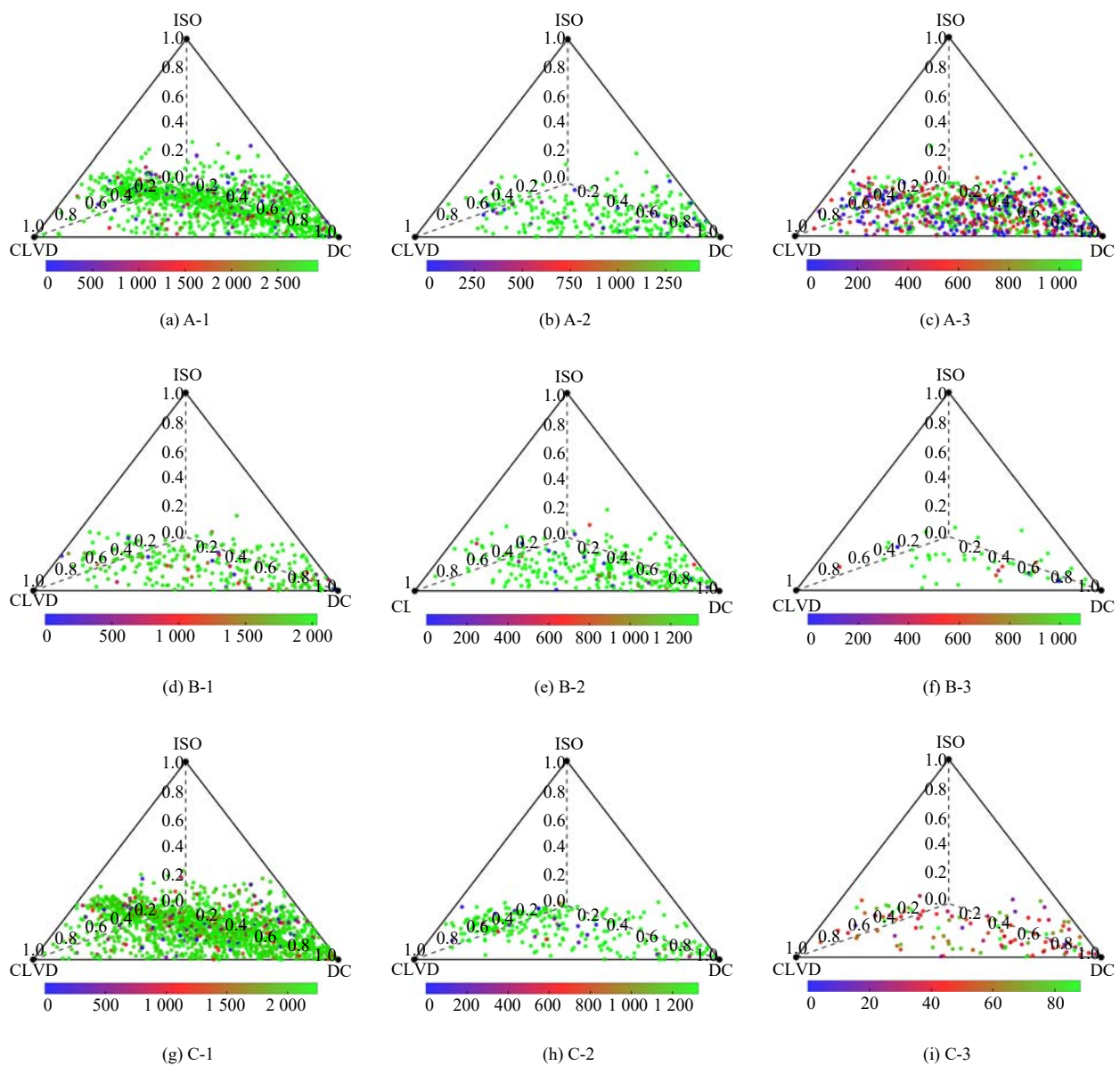
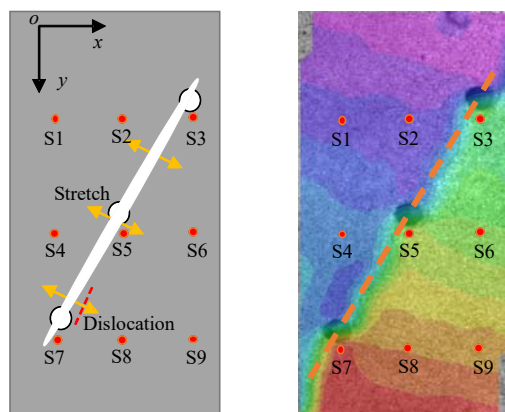


Fig. 8 Three-dimensional diagram of focal mechanism classification



(a) Crack analysis method

(b) Monitoring point layout

Fig. 9 Surface measurement points and crack expansion

To obtain the characteristics of rock surface fracture and crack propagation, data monitoring points were arranged in the potential fracture zone, specifically, monitoring points S3, S5, and S7 were placed 2 mm below different cavities, while the remaining monitoring points were evenly distributed across the rock surface. This setup allows for capturing the real-time dynamic changes of the rock during the loading process. The analysis method is shown in Fig. 9(a), where the x -axis represents the horizontal direction and the y -axis represents the vertical direction. Horizontal and vertical interpolation can reflect the displacement and opening trends during the rock fracture process. The horizontal direction is positive to the right, and the vertical direction is positive downward. The displacement data from each monitoring point are extracted to generate real-time displacement and differential change curves of the rock under various

loading rates and disturbances.

4.1 Rock surface fracture-ejection evolution law

To further investigate the differences in stress-induced crack development, rockburst, and surface spalling of porous rocks under varying loading rates, this study examined the crack propagation evolution and ejection failure characteristics during rock failure. As shown in Fig. 10, while the failure patterns exhibit minor variations

across different loading rates, they show significant differences depending on the number of cavities. The findings reveal a strong correlation between failure modes and number of cavities, categorizing rock failure into three types: type I, predominantly tensile failure with localized shear failure; type II, a combination of tensile and shear failure, with shear failure being dominant; and type III, primarily shear failure.

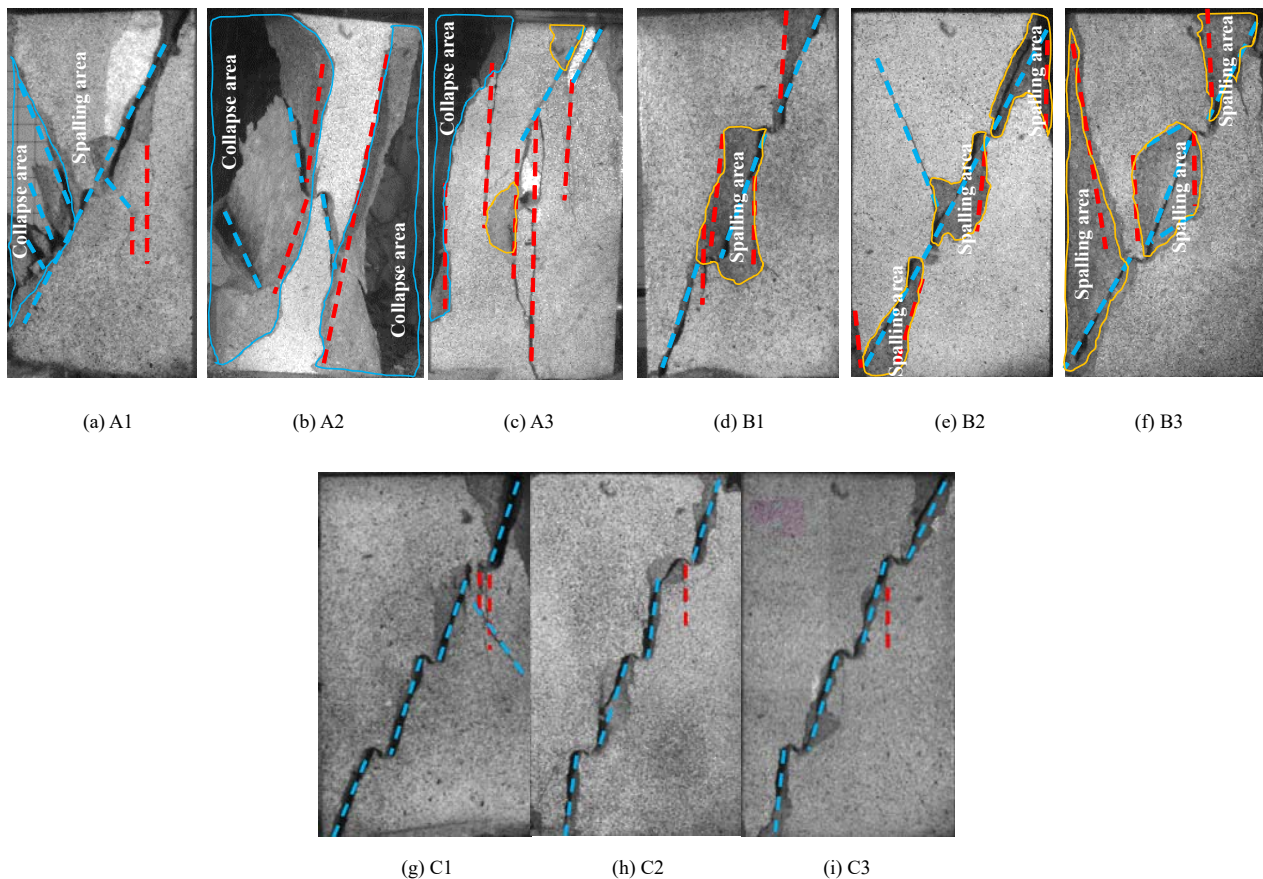


Fig. 10 Final failure morphology of rock

During the experiments, type I failure was characterized by minor surface spalling, accompanied by the ejection of relatively large rock fragments. As the loading rate increased, surface spalling disappeared, and the dominant failure mode transitioned from shear failure to tensile failure. In type II failure, slight surface spalling was observed, primarily in the central region of the rock, along with minimal ejection. Type III failure exhibited a distinct shear-cutting mode, with minor tensile failure occurring near the first upper pore and slight surface spalling around the pore, but no noticeable ejection was observed. Regardless of the loading rate, as the number of cavities increased, the failure showed a clear gradient along the pore direction, with both surface and internal damage decreasing. This suggests that an optimal number of cavities can effectively serve as stress-relieving structures, reducing the overall failure intensity.

From the experimental results, it was observed that

UCS of single-cavity rock was highest when the loading rate was 0.1 mm/min, denoted as σ_z . The UCS of other rock samples under different conditions was denoted as σ_c . The ratio of peak strength to maximum UCS (σ_c/σ_z) was calculated for various conditions. As shown in Fig. 11, the average σ_c/σ_z values for types I, II, and III rock samples were 0.959, 0.765, and 0.687, respectively. In type I samples, the σ_c/σ_z value was relatively high at the crack initiation stage, and the crack development duration was short, meaning that fractures did not have sufficient time to fully propagate before the rock reached its peak strength. During the post-peak stress drop, secondary crack propagation caused deformation, leading to a continuous decrease in stress. Type II samples exhibited slightly lower σ_c/σ_z values than type I, with a marginally longer crack development phase and more pronounced pre-peak fractures. Type III samples had the lowest σ_c/σ_z values, as crack initiation was more extensive, leading to widespread

crack coalescence after reaching peak strength, ultimately resulting in global instability and a sharp stress drop. These findings suggest that the extent of crack development in different post-peak failure modes significantly influences the intensity of ejection and dynamic failure.

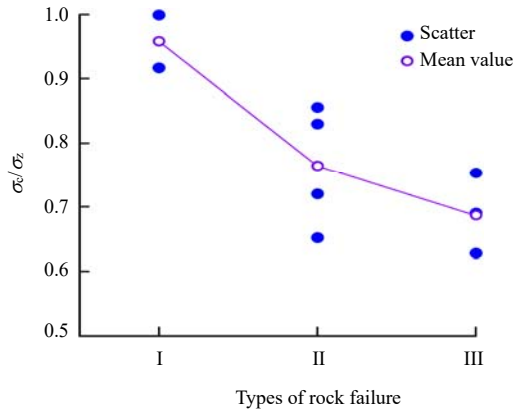


Fig. 11 Rock failure types

4.2 Dynamic strain evolution of rock samples

The distribution characteristics of horizontal and vertical strain in rock specimens are closely related to the number of cavities. The presence of cavities alters the stress transfer path, resulting in localized strain concentrations. The distribution patterns of horizontal and vertical strains reflect the rock's deformation mode and crack propagation. To systematically analyze these effects, strain behavior is examined under three conditions: single-cavity, double-cavity, and triple-cavity rock specimens.

Figures 12(a) and 12(b) illustrate the strain distribution in the single-cavity specimen. Where ε_{xx} represents the horizontal strain, ε_{yy} represents the vertical strain, and γ represents the shear strain. During the initial loading stage, the horizontal and vertical strain variations on both sides of the pore remain minimal, with small and relatively uniform strain values. The horizontal strain around the pore primarily exhibits compressive characteristics, while slight tensile strain appears on both sides of the pore along the loading direction due to stress redistribution. As loading progresses into the mid-to-late stage, the horizontal tensile strain around the pore intensifies significantly, with strain concentration primarily occurring on both lateral sides of the pore. Cracks tend to initiate in these high horizontal tensile strain zones and propagate horizontally. Meanwhile, the vertical strain above and below the cavity also increases considerably, gradually extending outward. Crack propagation primarily follows the loading direction, with the vertical strain exhibiting a steeper gradient than the horizontal strain. Just before failure, strain fluctuations become more pronounced, likely due to the irregular fragmentation and complex failure mechanisms of the

c-dynamcavity rock specimen. Experimental data indicate that the horizontal strain at monitoring point S4 reaches a peak value of 0.012, comparable to its vertical strain.

Figures 12(c) and 12(d) present the strain distribution in the double-cavity specimen. In the initial loading phase, the horizontal strain distribution in the double-cavity specimen exhibits some asymmetry. Due to the stress shielding effect, the horizontal strain values in the region between the pores remain relatively low, while horizontal tensile strain begins to appear on the outer sides of the pores, though with weak concentration. Compared to the single-cavity specimen, the concentration of vertical strain above and below the cavities in the double-cavity specimen is more pronounced. In the mid-to-late loading stage, particularly after 600 s, as the applied force further increases, the horizontal tensile strain in the region connecting the cavities intensifies significantly and gradually expands from the sides of individual pores toward the cavity-connection direction. This strain concentration effect facilitates crack coalescence between cavities, making the horizontal tensile strain region the primary pathway for crack propagation. Concurrently, vertical strain concentration extends along the loading direction, with peak values observed above and below the cavities. Additionally, vertical strain in the inter-cavity region also increases, suggesting that cracks may gradually coalesce along the loading axis. Just before failure, the strain at monitoring point S4 fluctuates, likely due to impending surface spalling in the rock specimen. Except for the spalling region, the horizontal and vertical strains in the double-cavity specimen remain below 0.05.

Figures 12(e) and 12(f) illustrate the strain distribution in the triple-cavity specimen. In the mid-to-late loading stage, horizontal tensile strain in the pore-connection region increases significantly, particularly in the central area where multiple pores intersect. Due to the uneven gradient of horizontal strain distribution, cracks predominantly propagate along the cavity-connection direction, influenced by horizontal tensile strain. Vertical strain reaches peak values in the cavity-connection region, especially along the loading direction, where the distribution of vertical strain is particularly prominent. Compared to the single-cavity and double-cavity specimens, the triple-cavity specimen exhibits minimal strain fluctuations before failure. This may be attributed to the increased number of cavities, which act as stress relievers while simultaneously reducing the rock's compressive strength, leading to abrupt failure.

4.3 Analysis of microstructure evolution characteristics and failure mechanism

The primary cause of rock strength loss is the propagation and penetration of microcracks. External disturbances significantly alter the microstructure within the rock and around pores, accelerating this failure process. To further reveal the microstructural response mechanism,

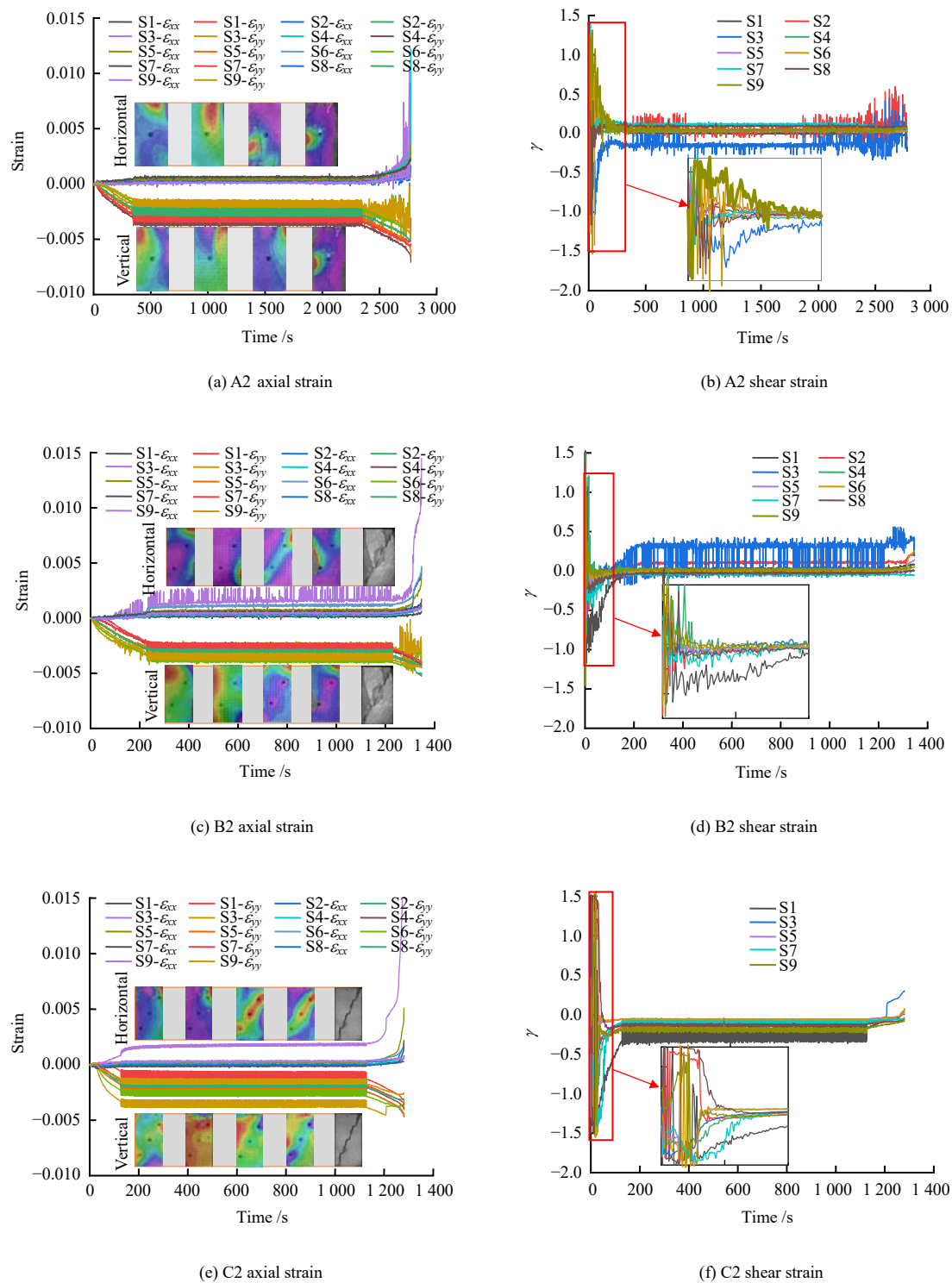


Fig.12 Strain fields in rock specimens with different numbers of cavities

this study used scanning electron microscopy (SEM) to observe the surface and cavity-surrounding microstructure of the damaged specimens, investigating the evolution of microcracks and pores in the rock under varying loading rates and cavity structures. Fig. 13 shows microscopic images of the specimen fracture surface obtained at an accelerating voltage of 8 kV and a magnification of 2 000 $\times$. As can be seen, the rock fracture is primarily characterized by intercrystalline and intracrystalline

fractures, with microcracks extending along grain boundaries or through grains, reflecting the stress concentration and microstructural damage characteristics of the rock mass during failure.

Under single-cavity conditions, the rock exhibits numerous microcracks after failure, with a relatively loose microstructure and relatively uniform pore distribution. Under double-cavity conditions, microcracks coexist with large cracks, and the rock surface roughness

increases significantly with increasing loading rate. The mineral skeleton becomes prominent, and local stress concentration is evident. Under triple-cavity conditions, the convergence of cavities on the rock fracture surface increases, forming a locally interconnected macroporous region. The degree of mineral particle fragmentation increases, and the skeleton structure is more exposed. The greater the number of cavities, the greater the degree of local disturbance in the rock, making it easier for microcracks to converge and expand into through-cracks. Furthermore, the increase in loading rate further enhances the destructive effect of dynamic disturbance on the microstructure, ultimately resulting in significant differences in the rock mass fracture morphology.

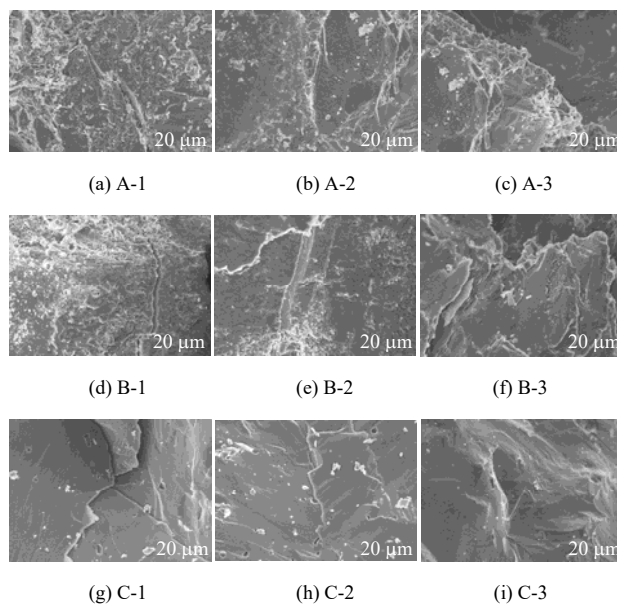


Fig. 13 Microscopic morphology of sample fracture

ImageJ image analysis software was used to statistically analyze the pore area of microcracks in SEM images to study the structural variations of microcracks on the rock surface. Appropriate grayscale values were selected for segmentation, and finally, area calculation was performed. The pore distribution extracted from the SEM images is shown in Fig. 14 (this section only analyzes samples A-1 to A-3, where the blue portion represents pores and the white portion represents the rock matrix).

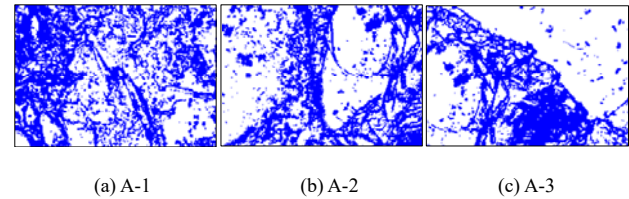


Fig. 14 SEM crack distribution

The pore data of the SEM images were statistically calculated to obtain the microcrack areas of the SEM images under different cavities and loading rates. The crack areas of the samples are shown in Table 2.

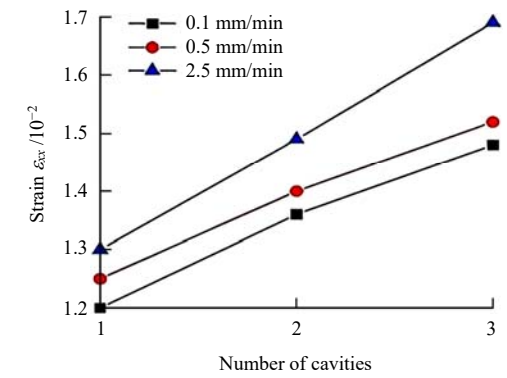
To clarify the correlation between microcrack propagation and the macroscopic strain field around the cavities at different loading rates, a micro-macroscopic analysis of the relationship between number of cavities and crack propagation was performed by combining SEM scanning and DIC test results. As shown in Fig. 15, the maximum horizontal strain gradually increases with increasing number of cavities in the rock. The strain around the cavities increases with increasing loading

Table 2 Crack areas of specimens

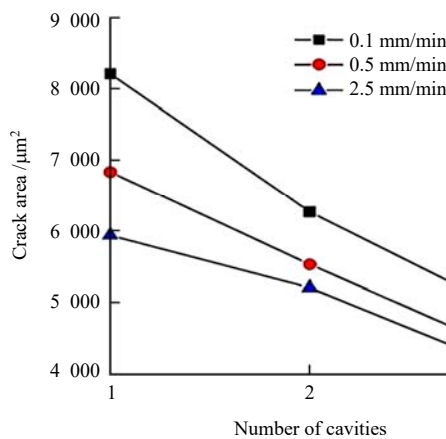
Serial number	A-1	A-2	A-3	B-1	B-2	B-3	C-1	C-2	C-3
Crack area/ μm^2	8 215.02	6 836.24	5 942.35	6 273.41	5 536.09	5 210.13	4 876.08	4 314.03	4 077.52

rate, reaching a maximum horizontal strain of 0.016 9. At a loading rate of 0.1 mm/min, compared with single-cavity rock, the horizontal strain rates of the double-cavity and triple-cavity rocks increase by 13.33% and 8.82%, respectively, with an average increase of 11.08%. At a loading rate of 0.5 mm/min, the horizontal strain rates of the double-cavity and triple-cavity rocks increase by 12% and 8.57%, respectively, with an average increase of 10.29%. At a loading rate of 2.5 mm/min, the horizontal strain rates of the double-cavity and triple-cavity rocks increase by 14.62% and 13.42%, respectively, with an average increase of 14.02%. As the number of cavities increases, the area of cracks around the cavities decreases, and the higher the loading rate, the smaller the crack area around the cavities. When the loading rate is 0.1 mm/min,

compared with single-cavity rock, the crack areas of double-cavity and triple-cavity rocks decrease by 23.64% and 22.27%, respectively, with an average decrease of 22.96%. When the loading rate is 0.5 mm/min, the crack areas of double-cavity and triple-cavity rocks decrease by 19.02% and 22.07%, respectively, with an average decrease of 20.55%. When the loading rate is 2.5 mm/min, the crack areas of double-cavity and triple-cavity rocks decrease by 12.32% and 21.75%, respectively, with an average decrease of 17.04%. At a loading rate of 0.1 mm/min, the pore area increases by 2.07% for every 1% increase in rock strain; at a loading rate of 0.5 mm/min, the pore area increases by 1.99% for every 1% increase in rock strain; and at a loading rate of 2.5 mm/min, the pore area increases by 1.26% for every 1% increase in rock strain.



(a) Relationship between number of cavities and strain field



(b) Relationship between the number of cavities and crack propagation

Fig. 15 Relationship between the number of cavities, crack propagation and strain field

5 Conclusion

(1) The peak strength of sandstone shows a nonlinear increase with rising loading rates but decreases as the number of cavities increases. At high loading rates, the overall load-bearing capacity of the rock improves. However, in multi-cavity samples, the effect of local stress concentration becomes more pronounced, leading to a reduction in failure strength.

(2) The evolution of cracks in sandstone is influenced by both cavity distribution and loading rate. AE analysis reveals distinct stages in the processes of crack initiation, propagation, and ultimate failure. Failure in single-cavity sample is primarily dominated by localized tensile fractures, whereas double-cavity and triple-cavity samples exhibit more complex fracture paths, showing an interplay between shear and tensile failure mechanisms. This suggests that the number and spatial distribution of cavities play a crucial role in determining local stress concentration and crack propagation patterns within the rock.

(3) Experimental results indicate that at low loading rates, dynamic strain fluctuations are relatively minor. In contrast, at high loading rates, sandstone exhibits

stronger dynamic responses, with significantly intensified AE activity. A sharp increase in AE events prior to failure marks an accelerated phase of crack nucleation and propagation, ultimately leading to global instability and catastrophic failure.

(4) The macroscopic fracture morphology of the rock is strongly correlated with the number of cavities. The average ratio of peak strength to maximum uniaxial compressive strength (σ_c/σ_z) for failure types I, II, and III is 0.959, 0.765, and 0.687, respectively. In type I failure, minor surface spalling occurs, accompanied by severe ejection events, with relatively large ejected fragments. In type II failure, slight surface spalling is also observed, predominantly in the central region of the rock sample, with localized minor ejection. In type III failure, mild spalling is found near the cavities, but no ejection events occur. These findings suggest that optimizing the upper and lower seam mining layout, rationally adjusting the rock support structure, and precisely controlling perturbation conditions are essential strategies for mitigating the risk of dynamic disasters in coal mines.

Data Availability

Data is available on request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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