

Study on *in situ* stress testing method based on Kaiser effect of acoustic emission and COMSOL simulation

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Abstract *In situ* stress testing can improve the safety and efficiency of coal mining. Identifying the Kaiser effect point is vital for *in situ* stress calculations; however, the *in situ* stress calculation is limited by the rock sampling angle. Here, the Kaiser effect point identification theory is established and applied to the Xuyong Coal Mine. Uniaxial compression and acoustic emission experiments were carried out on sandstone with 6 sampling directions. Furthermore, COMSOL simulation is applied to study the *in situ* stress distribution in the coal mine to verify the calculation accuracy. The results are as follows. 1) The failure mode of non-bedded and vertical-bedded rocks is primarily tensile shear failure with obvious brittleness in mechanical and acoustic emission characteristics. Shear slip along the bedding plane is the primary failure mode of inclined-bedded rock. Additional take-off points exist in the AE count curve. 2) The Kaiser point identification method based on the variation of AE count curve parameters Δt_i and τ_i can effectively calculate the *in situ* stress. According to the numerical value of Kaiser point and sampling direction, the *in situ* stress of the conveyor roadway in the Xuyong Coal Mine was calculated as $\sigma_1 = 22.81$ MPa, $\sigma_2 = 10.87$ MPa and $\sigma_3 = 6.14$ MPa. 3) By the COMSOL simulation study, it was found that a stress concentration zone of 16.13 MPa exists near the two sides roadway. Compared with the Kaiser effect method, the deviation rates of the three-direction principal stress calculated by COMSOL were all less than 5%. This verifies that the *in situ* stress calculation by Kaiser effect in this study can be applied to the Xuyong Coal Mine.

Keywords Kaiser effect point, *in-situ* stress calculation,

Xuyong Coal Mine, uniaxial compression, acoustic emission, COMSOL simulation

1 Introduction

In situ stress is also called initial rock stress, which is the fundamental factor leading to the deformation and failure of engineering rock mass (Liu et al., 2017; Radwan et al., 2021). *In situ* stress calculation is crucial to the study of rock engineering design. In recent years, underground rock engineering (Yin et al., 2015), water conservancy and hydropower engineering (Yin et al., 2012), civil engineering (Jiang et al., 2010), and other production activities are constantly expanding scale and developing toward greater depths (Ye et al., 2021). The equilibrium state of ground stress is likely to be disturbed during any of these activities, thus, causing instability collapse, reservoir earthquake, rock burst, roof collapse, floor water inrush, and other geological disasters (Xie et al., 2019; Yu and Mao, 2020). It is critical to accurately measure the *in situ* rock mass stress and consider the influence of geological conditions or engineering excavation on natural stress to solve various engineering and geological problems.

Currently, various *in situ* stress testing methods are being widely used, such as hydraulic fracturing (HF) (Subrahmanyam, 2019), strain recovery (Zhao et al., 2015), stress relief (Krietsch et al., 2019), and acoustic emission (AE) (Wu et al., 2019). The HF method can more accurately measure the rock stress in the deeper area than the others, but it is only suitable for the stress test of relatively intact rock masses (Lai et al., 2019). The measurement accuracy of the strain recovery method is greatly affected by rock strain factors (such as

temperature, rock anisotropy, etc.), and the measurement accuracy is low (Liu et al., 2015). The stress relief method is suitable for open spaces where technicians can enter and perform construction measurements. In the AE method, the *in situ* stress can be estimated only by obtaining the core of the corresponding measuring point for the AE test (Heimisson et al., 2015). The AE method is widely used in underground engineering due to its advantages of easy operation and low price (Liu et al., 2018; Sause et al., 2019).

In recent years, the Kaiser effect of rock to determine the original rock stress has been widely used in engineering. When the rock stress exceeds the previous maximum stress, the AE activity increases significantly, accompanied by a sharp increase in cumulative AE counts (Tham et al., 2005; Nian et al., 2016). The stress at this time can be considered as the original rock stress. However, the Kaiser effect also has limitations. Because there are many abrupt points of cumulative AE counts during rock loading, the selection of Kaiser effect points is subjective (Ganne et al., 2007). Second, the Kaiser effect method to calculate the principal stress requires an exact angle of rock sampling. However, most construction sites, such as underground roadways, are manually sampled, and the sampling angle cannot be accurately controlled (Yokoyama et al., 2014), contributing to deviations in the calculation results of principal stress. Therefore, establishing a new Kaiser effect theory is necessary, which can effectively identify the Kaiser effect points and not be affected by rock sampling angle.

Current studies on *in situ* stress of AE test primarily focus on the effect of loading rates, temperature, water content, and other factors on the Kaiser effect point (Li et al., 2022). However, few studies have been conducted on effectively identifying Kaiser points and reducing the influence of sampling angle on the calculation accuracy of principal stress (Bai et al., 2018). Meng et al. (2019) performed tests on uniaxial cyclic loading and unloading of rocks and AE characteristics under different horizontal stresses and loading rates. They demonstrated that the horizontal stress affects the Kaiser effect more than the loading rate. Li et al. (2019a) studied the influence of loading rate on the AE of three rock types. The test results show that the loading rate significantly affects the Kaiser effect of brittle rock, but less affects the soft plastic rock. Chen et al. (2012) conducted uniaxial compression and AE on granite tests after heat treatment at 20°C–1200°C and collected AE signals. It was found that 300°C is the threshold value of rock Kaiser effect point stress reduction. The rock heat-treated at 600°C–1200°C has obvious brittle-plastic transition, which leads to the time delay of the Kaiser effect point. Xiao et al. (2021) analyzed the real-time total stress-strain-AE count curves of red sandstone in a temperature range of 20°C–900°C. The high-temperature thermal expansion effect contributes to the stone-rock void

expansion and increases the abrupt change point of AE count.

The difficulty of judging Kaiser effect points has increased. Zhang and Chen (2010) compared the AE properties of uniaxial compression of sandstones with three water contents. As the water content increases, the AE activity also becomes denser, and the Kaiser point appears earlier in the time domain. Miao et al. (2016) conducted cyclic loading and unloading experiments on granite with different water contents. The increased water content develops the rock lithology from brittleness to ductility, which makes the rock enter the stage of damage acceleration transition earlier. Accordingly, the number of Kaiser suspected points is reduced and appear earlier.

The *in situ* stress calculation method is improved in this study, aimed at the abovementioned problems. First, based on the influence law of internal rock structure on Kaiser effect point discrimination, a comprehensive discrimination theory of Kaiser effect points is established. The theory is competent in identifying Kaiser effect points for rocks at any sampling angle and free from interference from take-off points of other AE counts curves. Then, based on the elastic rock mechanics principle, a new calculation method of the principal stress in three directions of rock is established. After that, sandstone was collected from a mining roadway of the Xuyong Coal Mine in south-eastern Sichuan Province. Uniaxial compression and AE tests were conducted to analyze the mechanical failure mechanism and acoustic emission characteristics of the samples. Finally, *in situ* stress in the geological field was calculated by COMSOL simulation, and the accuracy of the *in situ* stress calculation results was verified by combining it with the laboratory test results.

2 Improved *in situ* measurement principles

2.1 Kaiser effect identification theory

When rock is under a load, the AE count may have multiple sudden increases to varying degrees (Jin et al., 2009). Thus, there may be multiple suspected Kaiser effect points (Fig. 1). Therefore, the effective identification of Kaiser effect points is the key to *in situ* stress measurements. The study deduces a new method for Kaiser points identification. Rocks are elastoplastic materials, and reloading produces AE signals after stress relief (Damani et al., 2018). Only minor AE signals are generated when the rock load does not reach the maximum value in the geological history. If the maximum load is reached, many acoustic emission signals begin to generate (He et al., 2019). Then there is a sudden increase point with a large slope on the time-AE count curve, the take-off point. Based on the above information, the time-cumulative AE count curve in the rock failure process can be processed as follows:

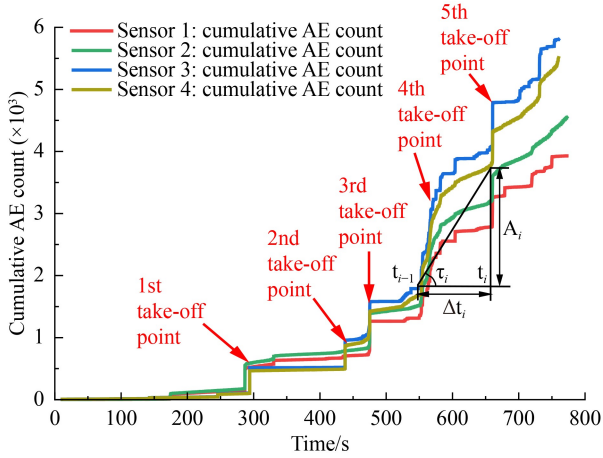


Fig. 1 Acoustic emission AE counts with take-off points (referring to rock sample with an angle $Y \angle 55^\circ Z$).

$$\begin{cases} \Delta t_i = t_i - t_{i-1} \\ k_i = A_i / \Delta t_i \\ \tau_i = \arctan k_i \end{cases}, \quad (1)$$

where t_i is a point in time of the time-cumulative AE count curve; A_i is the ring count of the curve at time t_i ; k_i is the inclination angle of the curve; τ_i is the inclination of AE curve ($^\circ$); Δt_i is the time difference of AE ringing count, s.

Δt_i represents the AE signal time characteristics during the rock compression process. The smaller the Δt_i value, the smaller the fluctuation range, indicating that the AE in the corresponding time range is more frequent. τ_i can represent the tilt of the time-cumulative AE count curve. If τ_i is close to 90° , it indicates a sharp increase in AE count at the corresponding time, as shown in Fig. 1.

Therefore, if the curve Δt_i is small and the τ_i is close to 90° at t_i , the AE frequency is high and the AE count increases significantly at this time. It fits the definition of a Kaiser point. Note that if τ_i is large (say 80°) but has a significant deviation from 90° , it cannot be regarded as a Kaiser point. Because when a Kaiser point occurs, the AE count increases. The slope of the AE count curve is also close to 90° .

Therefore, the location of Kaiser point can be found according to Δt_i and τ_i . The specific steps are as follows.

1) The Kaiser effect point time interval is roughly determined over the time-cumulative AE count curve obtained in the uniaxial compression test.

2) The Δt_i and τ_i are obtained by processing the AE real-time count over Eq. (1).

3) According to the curve of Δt_i – τ_i –stress–time, Kaiser effect point can be found within the time interval determined in the first step.

2.2 Principal stress calculation of *in situ* stress

In the three-dimensional stress field, the six components

of *in situ* stress ($\sigma_x, \sigma_y, \sigma_z, \tau_{xy}, \tau_{xz}, \tau_{yz}$) act at infinity (Lavrov, 2003). The direction and magnitude of the *in situ* stress can be calculated from its 6 components. The Kaiser effect can calculate the maximum historical stress of a rock specimen (Alkan et al., 2007). However, the *in situ* stress calculation by the Kaiser effect requires rock sampling from 6 specific angles. Due to the complex construction site conditions, such as coal mines and roadways, angle deviations inevitably occur, resulting in increased errors in the calculation results (Li et al., 2019b). Based on this, this study proposes an improved *in situ* stress calculation method based on the Kaiser effect. This method can calculate the *in situ* stress under any rock sampling angle to avoid the *in situ* stress calculation errors caused by sampling angle deviation.

2.2.1 Shear stress distribution of the tetrahedral element

The stress distribution on each surface of tetrahedral OABC is shown in Fig. 2 according to the elastic mechanical principle (Zhang et al., 2018; Zhu et al., 2018). The area of plane ABC is S , the principal stress is $T^{(n)}$, and the direction vectors of the outer normal line n are α_x, α_y , and α_z , respectively. The areas of plane OBC, OAC, and OAB are $S\alpha_x, S\alpha_y$, and $S\alpha_z$, respectively, and the corresponding stresses are $-T^{(1)}, -T^{(2)}$, and $-T^{(3)}$, respectively.

At the *in situ* stress test point, the balance equation of partial stress and principal stress of the micro-element is

$$T^{(n)}S - (T^{(1)}S_1 + T^{(2)}S_2 + T^{(3)}S_3) + f \cdot Sh/3 = 0, \quad (2)$$

where h is the vertical distance from point O to surface ABC; f is the volume force of tetrahedral element OABC; $Sh/3$ indicates the volume of the tetrahedral unit OABC. The $f \cdot Sh/3$ can be ignored when the tetrahedron OABC is an infinitesimal base unit. Eq. (2) can be transformed into:

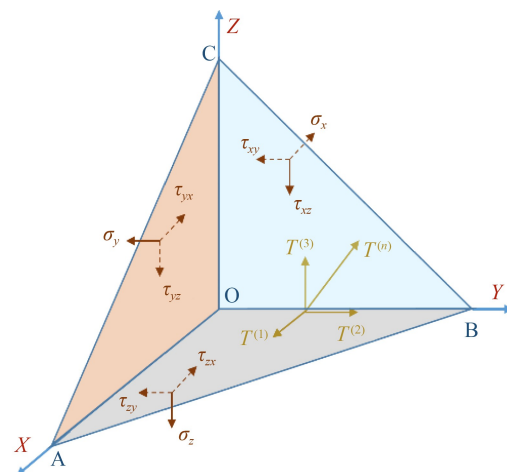


Fig. 2 Stress distribution of tetrahedron.

$$T^{(n)} = T^{(1)}\alpha_x + T^{(2)}\alpha_y + T^{(3)}\alpha_z. \quad (3)$$

The plane ABC stress vector can be decomposed into stress components along three coordinate axes:

$$\begin{cases} T^{(1)} = \sigma_x e_x + \tau_{yx} e_y + \tau_{zx} e_z \\ T^{(2)} = \tau_{xy} e_x + \sigma_y e_y + \tau_{zy} e_z \\ T^{(3)} = \tau_{xz} e_x + \tau_{yz} e_y + \sigma_z e_z \end{cases} \quad (4)$$

Substituting Eq. (4) into Eq. (3), gives

$$T^{(n)} = T^{(1)}e_x + T^{(2)}e_y + T^{(3)}e_z, \quad (5)$$

where

$$\begin{cases} T^{(1)} = \sigma_x \alpha_x + \tau_{yx} \alpha_y + \tau_{zx} \alpha_z \\ T^{(2)} = \tau_{xy} \alpha_x + \sigma_y \alpha_y + \tau_{zy} \alpha_z \\ T^{(3)} = \tau_{xz} \alpha_x + \tau_{yz} \alpha_y + \sigma_z \alpha_z \end{cases} \quad (6)$$

where matrix $\begin{bmatrix} \sigma_x & \tau_{yx} & \tau_{zx} \\ \tau_{xy} & \sigma_y & \tau_{zy} \\ \tau_{xz} & \tau_{yz} & \sigma_z \end{bmatrix}$ is the stress component of tetrahedral element OABC.

Substituting Eq. (6) into Eq. (5), gives

$$T^{(n)} = \sigma_x \alpha_x^2 + \sigma_y \alpha_y^2 + \sigma_z \alpha_z^2 + (\tau_{xy} + \tau_{yx}) \alpha_x \alpha_y + (\tau_{xz} + \tau_{zx}) \alpha_x \alpha_z + (\tau_{yz} + \tau_{zy}) \alpha_y \alpha_z. \quad (7)$$

According to Eq. (7), if the stress component matrix of OABC is known, the normal stress on the oblique section of ABC can be calculated. If the rock mass is considered as an elastic medium with a continuous mean, then $\tau_{xy} = \tau_{yx}$, $\tau_{yz} = \tau_{zy}$, and $\tau_{xz} = \tau_{zx}$. The shear stress values can be obtained by calculating the stress component matrix. The OXY plane stress distribution is taken as an example, as shown in Fig. 3, to show how to obtain the shear stress values on the OYZ, OXZ, and OXY planes.

Assuming that the angle between principal stress $\sigma_{x\theta y}$ and X axis is θ , the relation between principal stress and shear stress τ_{xy} on plane XOY is as follows:

$$\sigma_{x\theta y} = \sigma_x \cos^2 \theta + \sigma_y \sin^2 \theta + \tau_{xy} \sin 2\theta. \quad (8)$$

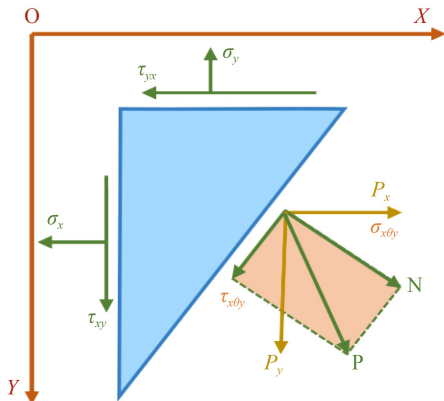


Fig. 3 Stress distribution of plane OXY.

Therefore, the following relations can be obtained:

$$\begin{cases} \tau_{xy} = \frac{\sigma_{x\theta y} - \alpha_x \cos^2 \theta - \alpha_y \sin^2 \theta}{2 \cos \theta \sin \theta} \\ \tau_{xz} = \frac{\sigma_{xyz} - \alpha_x \cos^2 \gamma - \alpha_z \sin^2 \gamma}{2 \cos \gamma \sin \gamma} \\ \tau_{yz} = \frac{\sigma_{y\psi z} - \alpha_y \cos^2 \psi - \alpha_z \sin^2 \psi}{2 \cos \psi \sin \psi} \end{cases} \quad (9)$$

where γ and ψ are the included angles between plane XOZ and Z axis, plane YOZ, and Y axis, respectively.

Therefore, when $\sigma_{x\theta y}$, σ_{xyz} , $\sigma_{y\psi z}$, θ , γ , and ψ are known, the shear stress of a certain point in rock space can be calculated.

2.2.2 Principal stress calculation method

According to the solid mechanic theory, the principal stress on the space microelement has the following characteristics. If the shear stress of a section on the micro-element body where the *in situ* stress measurement point O is located at zero, the stress vector $T^{(n)}$ is in the same direction as the external normal line n . The stress vector can be called the principal stress of the microelement (Schubnel et al., 2007; Zhang and Yin, 2014). Theoretical studies show that there are three principal stresses perpendicular to each other. According to the magnitude, they are respectively called the maximum, intermediate, and minimum principal stress (σ_1 , σ_2 , and σ_3).

If the principal stress at the *in situ* stress test point is represented as σ , its direction cosine is represented as α_1 , α_2 , and α_3 , respectively. Then

$$\begin{cases} T^{(1)} = \sigma \alpha_1 \\ T^{(2)} = \sigma \alpha_2 \\ T^{(3)} = \sigma \alpha_3 \end{cases} \quad (10)$$

Substituting Eq. (10) into Eq. (6) gives

$$\begin{cases} (\sigma_x - \sigma) \alpha_1 + \tau_{yx} \alpha_2 + \tau_{zx} \alpha_3 = 0 \\ \tau_{xy} \alpha_1 + (\sigma_y - \sigma) \alpha_2 + \tau_{zy} \alpha_3 = 0 \\ \tau_{xz} \alpha_1 + \tau_{yz} \alpha_2 + (\sigma_z - \sigma) \alpha_3 = 0 \end{cases} \quad (11)$$

Based on the calculation results of Eq. (11), the principal stress $\sigma_{1,2,3} \neq 0$. Furthermore, based on the principle of linear algebra, the principal and partial stress at the *in situ* stress test point satisfy the following requirements:

$$\begin{vmatrix} \sigma_x - \sigma & \tau_{yx} & \tau_{zx} \\ \tau_{xy} & \sigma_y - \sigma & \tau_{zy} \\ \tau_{xz} & \tau_{yz} & \sigma_z - \sigma \end{vmatrix} = 0. \quad (12)$$

Expanding Eq. (12) gives

$$\sigma^3 - I_1 \sigma^2 + I_2 \sigma - I_3 = 0, \quad (13)$$

where

$$\begin{cases} I_1 = \sigma_x + \sigma_y + \sigma_z \\ I_2 = \sigma_x \sigma_y + \sigma_y \sigma_z + \sigma_z \sigma_x - \tau_{xy}^2 - \tau_{yz}^2 - \tau_{xz}^2 \\ I_3 = \sigma_x \sigma_y \sigma_z + 2\tau_{xy} \tau_{yz} \tau_{zx} - \sigma_x \tau_{xy}^2 - \sigma_y \tau_{yz}^2 - \sigma_z \tau_{xz}^2 \end{cases} \quad (14)$$

The calculation equation of principal stress σ_i is as follows:

$$\begin{cases} \sigma_1 = 2\sqrt{-\frac{p}{3}} \cos \frac{w}{3} + \frac{1}{3} I_1 \\ \sigma_2 = 2\sqrt{-\frac{p}{3}} \cos \frac{w+2\pi}{3} + \frac{1}{3} I_1 \\ \sigma_3 = 2\sqrt{-\frac{p}{3}} \cos \frac{w+4\pi}{3} + \frac{1}{3} I_1 \end{cases} \quad (15)$$

where

$$\begin{cases} w = \arccos \left[-\frac{Q}{2} \sqrt{-\frac{4}{(p/3)^3}} \right] \\ p = -\frac{1}{3} I_1^2 + I_2 \\ Q = -\frac{2}{27} I_1^3 + \frac{1}{3} I_1 I_2 - I_3 \end{cases} \quad (16)$$

2.2.3 Principal stress direction calculation

The direction cosine of the principal stress vector with respect to axis Y and Z are m_i and n_i , respectively:

$$\begin{cases} m_i = B / \sqrt{A^2 + B^2 + C^2} \\ n_i = C / \sqrt{A^2 + B^2 + C^2} \end{cases} \quad (17)$$

where

$$\begin{cases} A = \tau_{xy} \tau_{yz} - (\sigma_y - \sigma_i) \tau_{zx} \\ B = \tau_{xy} \tau_{zx} - (\sigma_x - \sigma_i) \tau_{yz} \\ C = (\sigma_x - \sigma_i)(\sigma_y - \sigma_i) - \tau_{xy}^2 \end{cases} \quad i = 1, 2, 3 \dots \quad (18)$$

The azimuth angle β_i and inclination angle θ_i of the principal stress σ_i can be calculated as follows:

$$\begin{cases} \theta_i = \arcsin n_i \\ \beta_i = \arcsin (m_i / \sqrt{1 - n_i^2}) \end{cases} \quad (19)$$

where the principal stress inclination angle θ_i represents the included angle between the principal stress σ_i and the horizontal plane XOY (elevation angle when $\theta_i > 0$, depression angle when $\theta_i < 0$). The azimuth of the principal stress β_i represents the angle between the X axis and the principal stress σ_i projection on the horizontal plane (counterclockwise when $\beta_i < 0$ and clockwise when $\beta_i > 0$).

In summary, in the *in situ* stress test and calculation of Kaiser point, parameters of *in situ* stress measuring point should be obtained including σ_x , σ_y , σ_z , τ_{xy} , τ_{yz} , τ_{zx} , θ , γ , and ψ .

3 In situ stress testing experimental method

3.1 Sample preparation

Rock samples used in the test were taken from the conveyor roadway of Xuyong Coal Mine in Sichuan Province (Fig. 4(a)). The depth of the roadway is 386 m, the azimuth is 150° , and the inclination angle is 10° – 15° . The direction of the conveyor roadway (150° azimuth) is

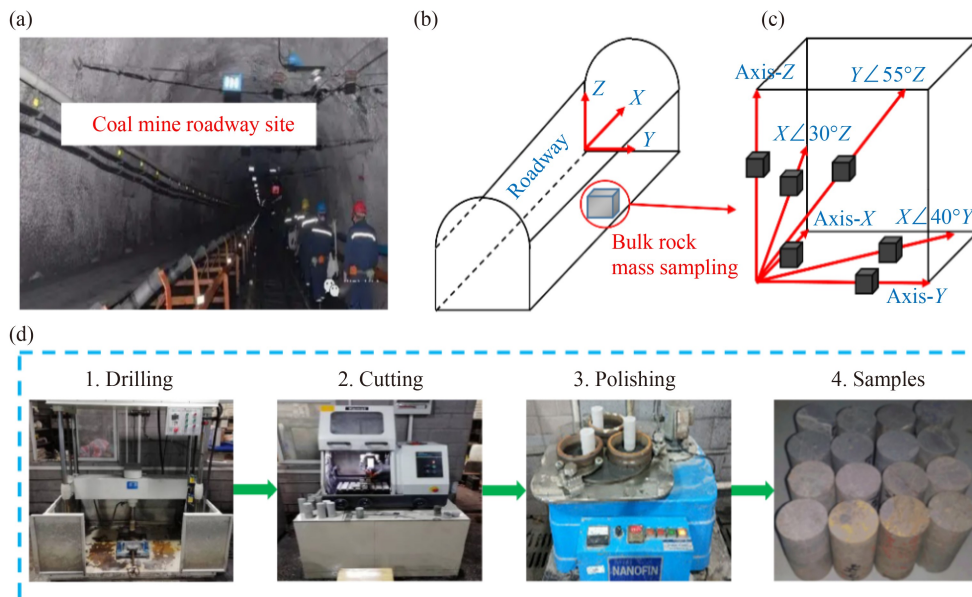


Fig. 4 Sampling and processing of rock specimens. (a) Rock specimens sampling site; (b) schematic diagram of field sampling; (c) specimens sampling directions; (d) Sample preparation process.

considered the X -axis. The direction perpendicular to the X -axis (240° azimuth) is considered the Y -axis. The XY plane normal direction is considered as the Z -axis (Fig. 4(b)). Rock was drilled from 6 directions X , Y , Z , $X\angle 40^\circ Y$, $X\angle 30^\circ Z$, and $Y\angle 55^\circ Z$ in the conveyor roadway (Fig. 4(c)). The physical parameters of rock samples are shown in Table 1. The sampling angle does not limit the Kaiser effect point discrimination in this study, so the selection of the sampling angle is random. The rock was sent to the laboratory and processed into a standard cylindrical sample with a size of $\varphi 50 \times 100$ mm (Fig. 4(d)). Both faces of these rock samples were carefully polished to ensure the unevenness error was less than 0.05 mm.

3.2 Test equipment and methods

The test equipment contains an AE monitoring and uniaxial loading system (Fig. 5). SHIMADZU AG-I250 servo material testing machine was the uniaxial loading system. The displacement control was used as a loading method with a loading speed of 0.01 mm/min. The AE monitoring system uses PCI-2 system with the AE signal acquisition threshold value of 40 dB. Before the experiment, rock samples were placed on the test table of the uniaxial loading system. Vaseline was applied on the surface of the acoustic emission probe as a coupling agent to avoid attenuation of the AE signal caused by air on the surface of the probe and specimen. Four acoustic emission probes were attached to the surface of the rock specimen. Before loading, a layer of butter was evenly spread on the upper and lower surfaces of the specimen to reduce the interference of the end effect on the AE signal. After setting the parameters of the AE monitoring and

uniaxial loading system, start the experiment with both systems simultaneously. The AE monitoring and uniaxial loading system were shut down when rock fracture occurred, and the stress decreased significantly (Fig. 6).

4 Analysis of tests results

4.1 Mechanical and AE characteristics analysis

A representative set of experimental results of uniaxial rock compression in six directions were chosen for characteristics analysis. The strain-stress curve of rock is shown in Fig. 6. The strain-stress curves represent different mechanical properties of rock. It can be seen that the rocks in the six directions have obvious anisotropy. Among them, rocks in X and Y -axis directions are not bedding, Z -Axis is vertical bedding, $X\angle 40^\circ Y$, $X\angle 30^\circ Z$, and $Y\angle 55^\circ Z$ are inclined bedding. The bedding structure of rock significantly influences its mechanical properties and energy dissipation process under compression (Panteleev et al., 2020). Therefore, this study analyzes the mechanical properties and acoustic emission variations of non-bedded and bedded rocks under uniaxial compression.

Through uniaxial compression and acoustic emission experiments, the compressive stress data of rock specimens in 6 directions and AE data from four groups of AE sensors are measured. Finally, the time-stress-cumulative AE count curves were obtained (Fig. 7). From Figs. 8(a)–8(c), with time increases, the 4 cumulative AE count curves maintain similar variation rules, and the total AE numbers remain consistent. By analyzing the rock

Table 1 The physical parameters of rock samples

Physical parameters	X -axis	Y -axis	Z -axis	$X\angle 40^\circ Y$	$Y\angle 55^\circ Z$	$X\angle 30^\circ Z$
Length/mm	100.1	100.0	99.9	100.0	99.8	100.1
Diameter/mm	49.9	50.0	50.0	49.9	50.1	49.9
Quality/g	495.47	488.32	495.09	487.74	493.03	402.09
Density/(g·cm ⁻³)	2.531	2.487	2.524	2.494	2.506	2.054

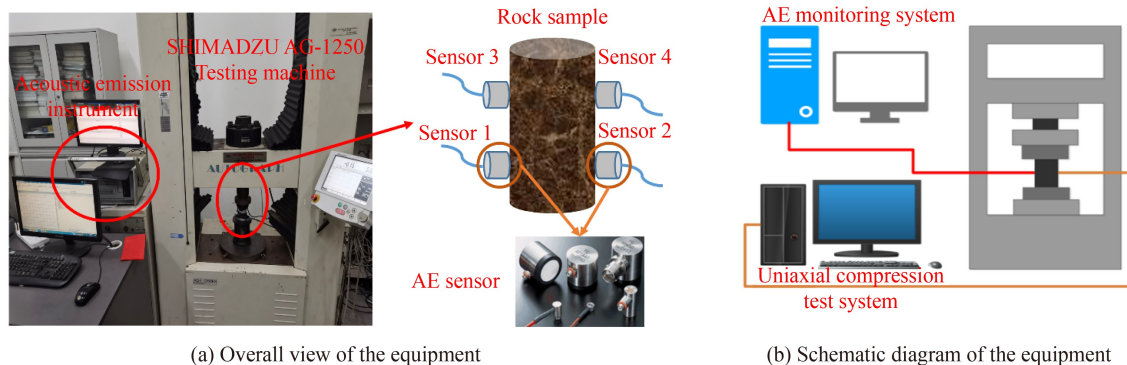


Fig. 5 Experimental equipment and principle. (a) Overall view of the equipment; (b) schematic diagram of the equipment.

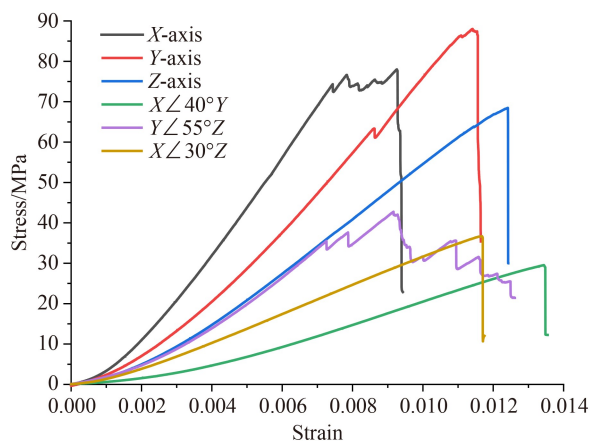


Fig. 6 Strain-stress curves of rock in 6 directions.

failure modes after the uniaxial compression test, the fracture angles of non-bedded and vertical-bedded rock specimens are larger. The main failure mode is longitudinal tensile shear failure. The strain-stress curve has an obvious stress drop phenomenon which shows brittle failure. The mechanical failure process is loading-complete failure.

The rock uniaxial compression process can be divided into four stages: elastic deformation, fracture initiation, fracture propagation, and stress failure. At the elastic deformation stage, the microcracks of rock specimens, including those between bedding layers, are compressed, and no new cracks appear or old cracks spread. Therefore, the cumulative AE count at this stage is small and grows slowly. At the fracture initiation stage, the rock appears to have plastic deformation. In the study, the rock sample is sandstone with high hardness. Therefore, at this stage, the expansion of rock micro-cracks releases more considerable strain energy, which accelerates the growth of AE count. When the stress value of rock reaches the maximum historical stress, the AE count take-off point, namely the Kaiser effect point, appears.

The cumulative AE count curve increases quickly with the fracture development acceleration at the fracture propagation stage. However, there are few AE count spikes like Kaiser point. This is because the development of fissures is accelerated but does not increase abruptly at this stage. Therefore, the release rate of strain energy is uniform. At the stress failure stage, the axial load gradually reaches its peak strength. Cumulative AE counts increase more rapidly and experiences unprecedented spikes at more than 99% of peak intensity. By analyzing the AE count variation process of non-bedded and vertical-bedded rock samples in the compression process, it can be concluded that the variation characteristic of cumulative AE count is ‘slow growth - uniform rapid growth - sharp growth’.

Figures 8(d)–8(f) shows the time-stress-cumulative AE count curve of inclined-bedded rock samples. The four AE counting curves of the same rock sample are close in

variation trend but differ significantly in quantity. In the four stages of uniaxial compression, the variation trend of the AE count of rock with inclined bedding is similar to that of non-bedded and vertical-bedded rock. The cumulative AE count curve increases slowly at the elastic deformation stage, accelerates at the fracture initiation stage, further accelerates in the fracture propagation stage, and increases sharply in the stress failure stage. However, the cumulative AE count of inclined-bedded rock shows a step-like upward trend several times. This is due to the difference in internal damage mechanism between non-bedded, vertical-bedded, and inclined-bedded rock specimens under mechanical action.

The failure mode of inclined-bedded rock specimens is mostly slip-shear failure along the bedding plane. By analyzing the damage results of rock after loading, it is found that the rock mass after mechanical loading instability has two approximate parallel shear bands, and the shear plane is scratched. The failure process of rock specimens is loading - local slip shear failure - loading - shear zone instability, and rock specimen failure. During the fracture initiation and propagation stage, multiple local slip failures along the bedding plane occur with energy accumulation. Therefore, the strain energy of rock specimens is released numerous times, and the cumulative AE curve also has several sudden increases. Thus, the AE counting curve presents several step-like upward trends. The damage to the inclined-bedded rock is mainly concentrated in a shear zone parallel to the bedding plane. However, the longitudinal shear fracture plane of non-bedded and vertical-bedded rock runs throughout the specimen. Overall, the AE counts of the inclined-bedded rocks vary significantly in space.

4.2 Kaiser effect point discrimination

Determining the Kaiser effect point is key to *in situ* stress testing, which determines the accuracy of *in situ* stress calculation results. The determination of the Kaiser effect point is mainly based on the variation degree of AE characteristic parameters. However, this method is highly subjective, and significant errors can easily occur (Li et al., 2010). In recent years, in-depth research has been conducted on the phenomenon and proposed several Kaiser point discrimination methods. Zhao et al. (2018) constructed the relationship model between acoustic time difference and Kaiser stress point of rock samples. Sabanov (2018) proposed a method to determine the Kaiser point by correlating the dimension of the G-P algorithm. Chen et al. (2020) provided a genetic algorithm method to recognize the Kaiser effect point. The above research results contribute to the Kaiser point's quantitative judgment. However, the algorithms used are complex, and the efficiency of discriminating the Kaiser point is low. Therefore, this study focuses on the Kaiser effect point discrimination method proposed in Section

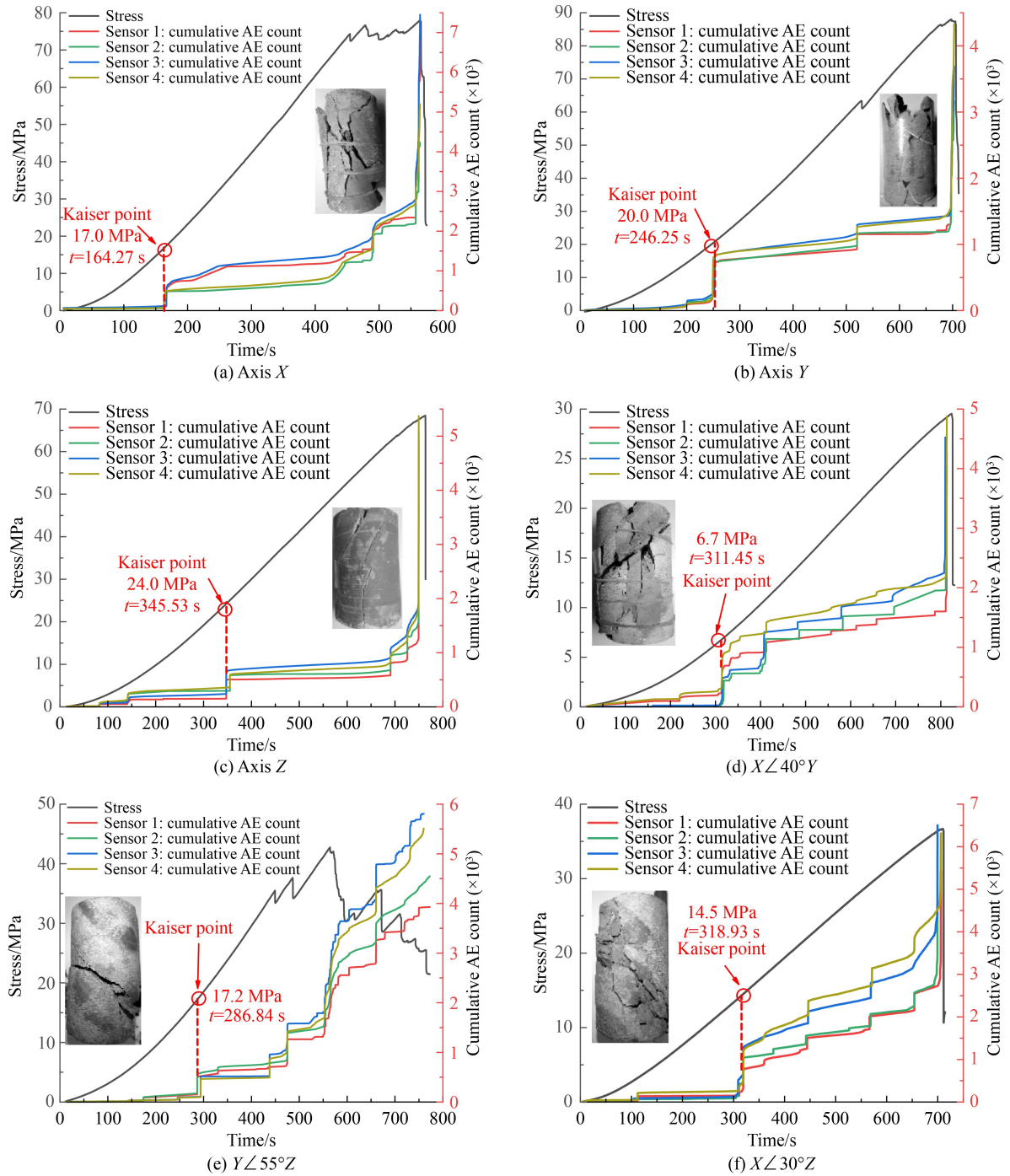


Fig. 7 Kaiser point discrimination based on curves of time, stress, and cumulative AE count. (a) Axis X; (b) Axis Y; (c) Axis Z; (d) $X\angle 40^\circ Y$; (e) $Y\angle 55^\circ Z$; (f) $X\angle 30^\circ Z$.

2.1, where the Kaiser point is determined comprehensively based on AE count time difference τ_i and time-cumulative AE count curve inclination angle Δt_i . The accuracy of Kaiser effect point identification in Section 4.1 is determined by AE parameters

The time- Δt_i - τ_i -cumulative AE count curve of the whole mechanical failure process of rock specimens is calculated by Eq. (1) (Fig. 8). To minimize the calculation error in space, the calculated data of rock

specimens in each direction all come from AE sensor 3. The parameters Δt_i and τ_i fluctuate with the increase in axial loading time. The amplitude of fluctuation is closely related to the damage and AE number of the rock. With the continuous loading of the axial load, the amplitude of ΔT_I wave decreases gradually, and the corresponding Δt_i value of τ_i wave time interval is closer to 90° . Therefore, the Kaiser point satisfies both the judgment conditions of Δt_i is close to 0 and τ_i is close to 90° .

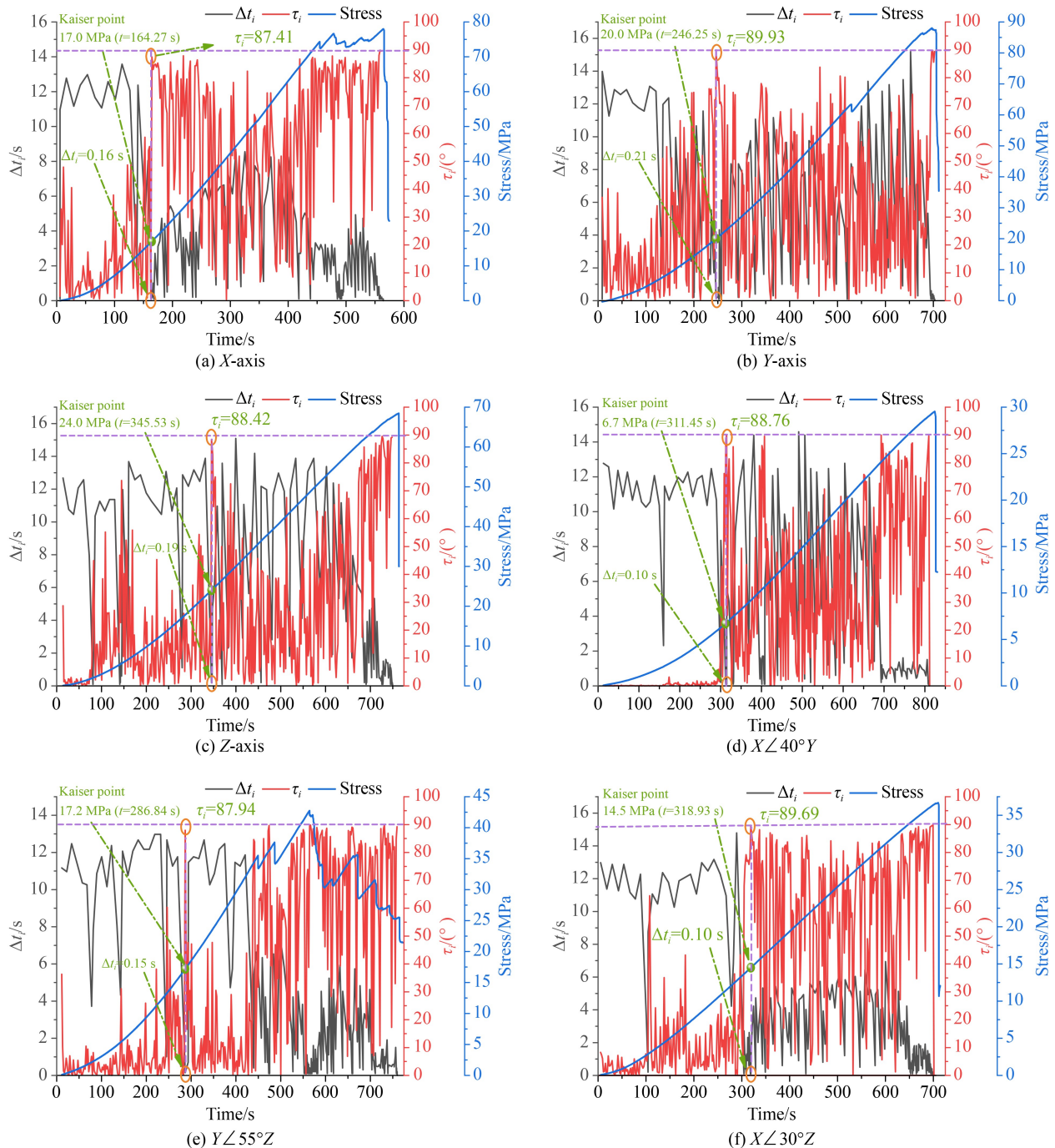


Fig. 8 Kaiser point discrimination basis based on curves of time, stress, Δt_i and τ_i of rock specimens. (a) Axis X; (b) Axis Y; (c) Axis Z; (d) $X \angle 40^\circ Y$; (e) $Y \angle 55^\circ Z$; (f) $X \angle 30^\circ Z$.

The Kaiser effect points of rock specimens in the 6 directions were determined according to the above comprehensive judgment method. Noteworthy, the slip shear failure along the bedding plane can also contribute to a sharp increase in the AE curve, which causes improper identification of the Kaiser point. Because the Kaiser point occurs when the rock is under maximum historical stress, there is often no obvious fracture development in the rock at this time. However, when the

number of AE increases sharply due to the shear slip of bedding, the development of rock cracks is accelerated, and even macroscopic cracks appear. Therefore, the first point that satisfies the criteria, which are Δt_i is close to 0 and τ_i is close to 90° , and can be regarded as the Kaiser point.

The specimen in the X-axis direction in Fig. 8(a) is used for illustration. When $t = 164.27$ s, the numerical point that conforms to the above criteria appears first.

Simultaneously, $\Delta t_i = 0.16$ s and $\tau_i = 87.41^\circ$. The stress value of the rock specimen is 17.0 MPa. This point is the Kaiser point along the X axis. After that, points meeting the above criteria appear in the fracture propagation and stress failure stage, called Kaiser suspected points. At this point, the fracture development degree of rock is large, and the cumulative AE counting curve appears to have multiple take-off points. Therefore, the Kaiser suspected points in these stages cannot be regarded as actual Kaiser effect points.

Similarly, Kaiser effect points of rock specimens in other directions can be obtained by using this determination method (Table 2). The Kaiser effect point discrimination result is identical to Fig. 7, which proves the method's effectiveness. Substituting Kaiser point calculation results into the calculation equations of *in situ* stress in Section 2.2, and the *in situ* stress calculation results by the Kaiser effect are obtained (Table 3). The maximum and minimum principal stresses are close to the horizontal direction, and the intermediate principal stress is close to the vertical direction. In engineering, the ratio of horizontal stress (σ_1) to vertical stress (σ_2) is regarded as the lateral pressure coefficient. In this study, the lateral pressure coefficient is 2.01, indicating that the original rock stress of this roadway is dominated by tectonic stress.

4.3 *In situ* stress calculation based on COMSOL

4.3.1 Calculation model establishment

To verify the accuracy of the calculated results of ground

Table 2 Kaiser effect point parameters

Drilling direction of rock specimen	Time/s	Δt_i /s	$\tau_i/(^\circ)$	Stress/MPa
X -axis	164.27	0.16	87.41	17.0
Y -axis	246.25	0.21	89.93	20.0
Z -axis	345.53	0.19	88.42	24.0
$X \angle 40^\circ Y$	311.45	0.10	88.76	6.7
$Y \angle 55^\circ Z$	286.84	0.15	87.94	17.2
$X \angle 30^\circ Z$	318.93	0.10	89.69	14.5

Table 3 *In situ* stress results by the Kaiser effect

<i>In situ</i> stress	Values/MPa	Azimuth angle/($^\circ$)	Inclination angle/($^\circ$)
Maximum principal stress (σ_1)	22.81	162.35	-7.52
Intermediate principal stress (σ_2)	10.87	61.25	-81.65
Minimum principal stress (σ_3)	6.14	257.68	-13.56

stress, this study simulated the *in situ* stress at the rock sampling points at the Xuyong Coal Mine. The COMSOL simulation can effectively analyze the stress distribution regularly near rock sampling points and provide the theoretical basis for road safety protection work. Numerous studies have been published on rock mechanics simulation, but there is a lack of research on the distribution law of ground stress. Cao et al. (2022) verified the statistical damage constitutive rock mass model by COMSOL and MATLAB software. They determined that the stress distribution of round holes surrounding rock is circular under the same *in situ* stress. Zhang et al. (2022) solved the rock state damage variable, displacement, and pressure in hydraulic fracturing by COMSOL simulation. A permeability anisotropy model was established to characterize hydraulic fracturing of a coal seam. Basirat et al. (2021) developed a fracture fluid flow model in a filling well in COMSOL. The change rule of fracture radius in different fracturing stages was obtained.

According to the geological conditions of rock sampling points (referring to the roadway information presented in Section 3.1), a 3D model of $X \times Y \times Z = 80 \text{ m} \times 80 \text{ m} \times 80 \text{ m}$ was established using COMSOL, including a conveyor roadway with an inclination angle of 10° . The model grid contained 110372 units (Fig. 9(a)). The X -axis is the horizontal direction, ranging from -20 – 20 m; the Y axis is the horizontal direction perpendicular to the X axis, and with a 14° angle with the roadway, ranging from 0 to 40 m; the Z -axis is in the vertical direction ranging from -20 to 20 m.

As shown in Fig. 9(b), the model top is subjected to the overlying rock stress. Usually, the vertical stress gradient of the rock is 25–30 KPa/m (Lu et al., 2020), and the burial depth of the conveyor roadway in the Xuyong Coal

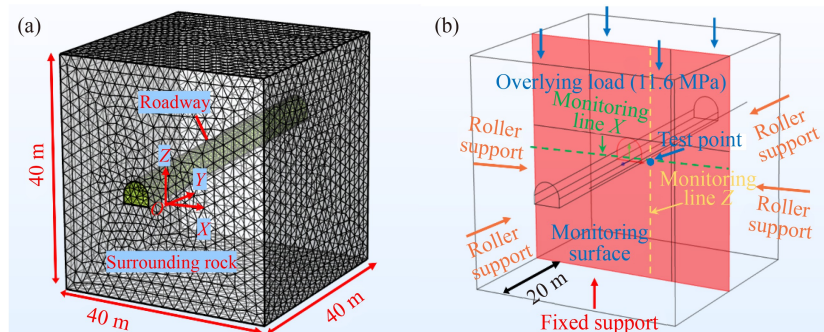


Fig. 9 Geometric physical model construction. (a) Meshing; (b) boundary condition.

Mine is 386 m. Therefore, the overlying pressure boundary load value was set as 11.6 MPa. The model bottom was applied with fixed constraint boundary, and the roller support was adopted for the other four sides. The physical and mechanical parameters of rock after experimental tests are shown in Table 4. The Mohr-Coulomb model was applied to calculate *in situ* stress.

A monitoring surface and two monitoring lines were added to the geometric physical model to study the *in situ* stress distribution around the rock sampling point. The monitoring plane was XOZ located at $Y = 20$ m. In the monitoring plane, there was a monitoring line parallel to the X -axis and Z -axis. The intersection of the two lines is the rock sampling point of the Kaiser effect, namely the *in situ* stress test point. The test point was close to the right arch foot of the roadway, with a horizontal distance of 1 m and a vertical distance of 0.5 m.

Table 4 Rock physical and mechanical parameters

Density/ ($\text{kg} \cdot \text{m}^{-3}$)	Elastic modulus/GPa	Poisson's ratio	Cohesion/ MPa	Friction angle/(°)	Tensile strength/MPa
2700	39	0.28	8	37	1.2

4.3.2 *In situ* stress calculation results analysis

The principal stresses calculation results on the monitoring surface are shown in Fig. 10. As the roadway trend in the calculation model is slightly inclined, the principal stress distribution presents weak asymmetry. The maximum, intermediate, and minimum principal stresses are in the shapes of ‘∞’, ‘+’, and square distribution, respectively. Three-directions principal stress is dominated by compressive stress. Small tensile stress exists in the shallow part of the roadway roof and floor. An obvious principal stress concentration exists at 1–5 m on both sides of the roadway. The test point is located in the main stress concentration area.

The principal stress difference of roadway surrounding rock presents a butterfly distribution (Fig. 10(d)). The main stress difference relief zone is the shallow part of the roadway roof and floor. There is a prominent concentration area of principal stress difference within 5 m on the roadway on both sides. The deeper the surrounding rock extends, the smaller the principal stress difference—the more significant the difference in

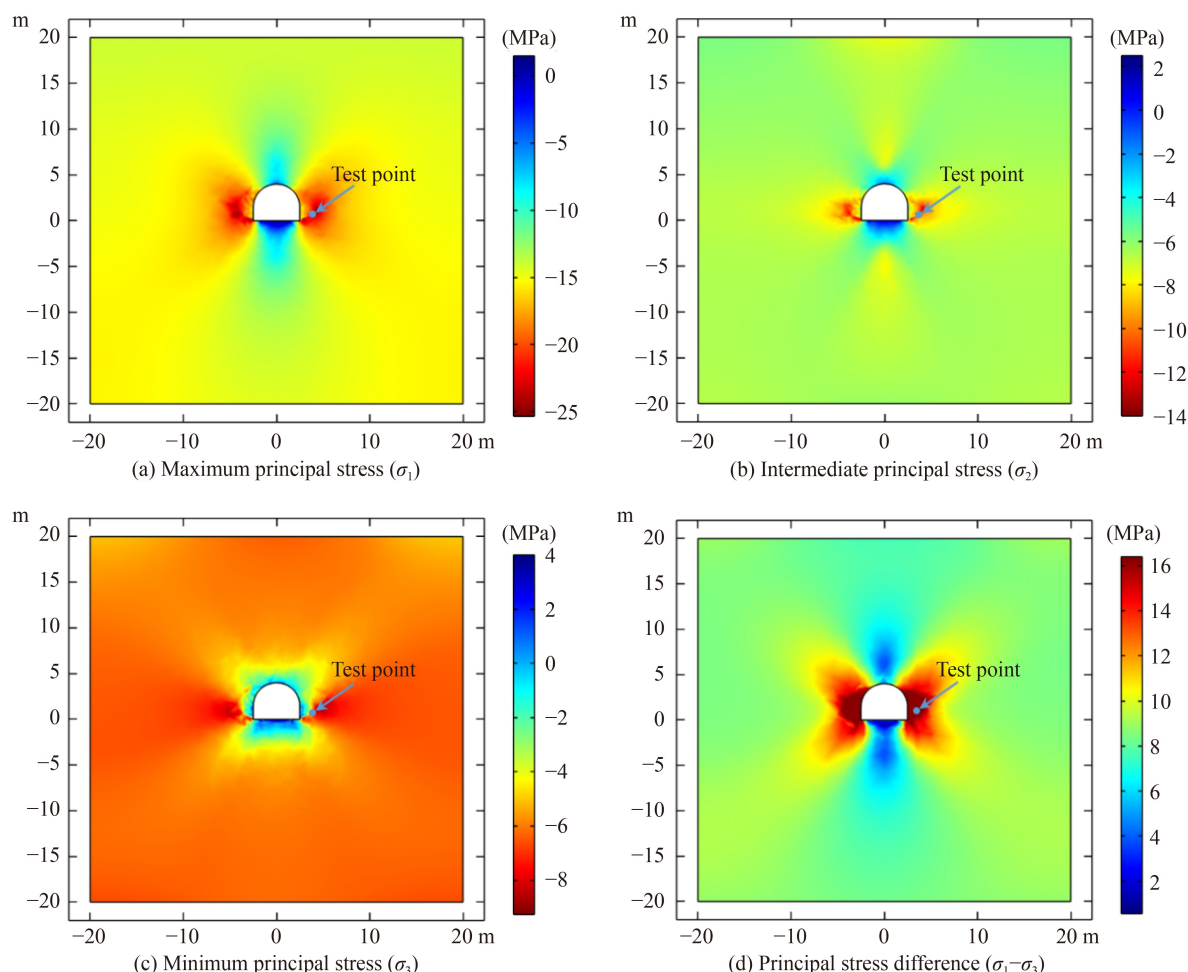


Fig. 10 Three principal stress distribution nephogram. (a) Maximum principal stress (σ_1); (b) Intermediate principal stress (σ_2); (c) Minimum principal stress (σ_3); (d) Principal stress difference ($\sigma_1 - \sigma_3$).

principal stress, the greater the possibility of rock failure. Therefore, the two sides of the roadway are more prone to collapse than the roof and floor. The safety protection work of the conveyor roadway in the Xuyong Coal Mine should focus on supporting the two sides.

To analyze the stress distribution in horizontal and vertical directions, the variation of principal stress and stress difference between the two monitoring lines and test point was studied (Fig. 11). The $-2.5\text{--}2.5\text{ m}$ range of the X monitoring line is the hollow area of the roadway, and no stress distribution exists. The stress and stress difference curves are humped. The stress increases within the $0\text{--}2\text{ m}$ range of the roadway's two sides, and the maximum value of the principal stress difference appears near the detection point. As the surrounding rock depth increases, the principal stress and the principal stress difference decrease and tend to be stable. The σ_2 and σ_3 finally approach, and the principal stress difference is approximately 8.5 MPa .

The $0\text{--}5\text{ m}$ range of the Z monitoring line is in the same horizontal plane as the roadway, called the parallel area. It contains the extreme point of principal stress and stress differences. The σ_3 curve has a basin shape with a single peak. When $Z = 0.5\text{--}3\text{ m}$, the principal stress difference is approximately the maximum of 16 MPa . Similar to the X monitoring line, the principal stress and the principal stress difference gradually stabilize away from the roadway. At the test point, the σ_1 , σ_2 , and σ_3 are 22.01 MPa , 10.46 MPa , and 5.88 MPa , respectively.

The *in situ* stress results calculated by COMSOL were compared with the Kaiser effect. Among them, the maximum principal stress of the deviation rate is: $|\sigma_{1ae} - \sigma_{1re}| / \sigma_{1re} \times 100\% = 4.42\%$. Where σ_{1ae} is the maximum principal stress σ_1 calculated by the Kaiser effect, and σ_{1re} is σ_1 obtained by COMSOL. The deviation rates of the three principal stresses are 4.42% , 3.92% , and 3.63% , respectively, which are all less than 5% . Therefore, the *in situ* stress calculation results based on the Kaiser effect in this study are effective.

5 Conclusions

The discrimination of the Kaiser effect points and the rock sampling direction are always complex problems in *in situ* stress calculations. In this study, a Kaiser point discrimination method based on AE count curve parameters Δt_i and τ_i is established, free from inaccuracies caused by the rock sampling direction. Taking the sandstones of the Xuyong Coal Mine as the research object, uniaxial and acoustic emission tests were performed to calculate the *in situ* stress. The COMSOL simulation was used to verify the accuracy of *in situ* calculation results. The distribution law of the three-direction principal stresses near the roadway is also studied. The main conclusions of this study are summarized as follows.

1) Under uniaxial compression, non-bedded, vertical-bedded, and inclined-bedded rocks exhibit different mechanical and AE characteristics. The analysis shows that the root cause of the different rules lies in the difference in the damage process inside the rock. The failure mode of the former is mainly longitudinal tensile shear failure. The strain-stress curve has an apparent stress drop phenomenon. The failure mode of the latter is mainly slip shear failure along the bedding plane. As the damage of inclined-bedded rocks is mainly concentrated in shear zones of parallel bedding planes, numerous spatial differences exist in AE counts.

2) The Kaiser effect points can be effectively identified without interference from the other take-off points of AE count curves based on the two criteria of AE count curve time difference Δt_i approaching 0 and inclination angle τ_i approaching 90° . In fracture initiation and propagation stages, the Kaiser points of rock samples appear in six sampling directions. The values, azimuth, and inclination angles of the three-direction principal stress were calculated as $\sigma_1 = 22.81\text{ MPa}$, $\sigma_2 = 10.87\text{ MPa}$, and $\sigma_3 = 6.14\text{ MPa}$. The lateral pressure coefficient of conveyor roadway in the Xuyong Coal Mine is 2.01 , indicating that the original

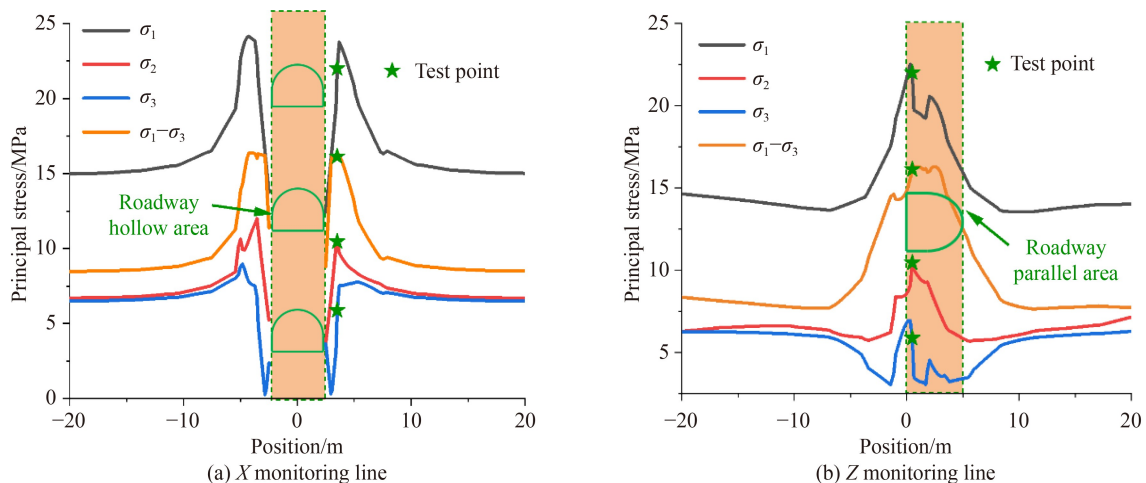


Fig. 11 Three principal stresses at the monitoring line. (a) X monitoring line; (b) Z monitoring line.

rock stress is dominated by tectonic stress.

3) The magnitude and distribution of *in situ* stress in roadway surrounding rock were studied by COMSOL simulation. The maximum, middle, and minimum principal stresses show ‘∞’, ‘+’, and square shape distribution, respectively. The principal stress difference of roadway surrounding rock shows butterfly shape distribution. The principal stress concentration is severe on the two sides of the roadway. Therefore, support needs to be provided to both sides of the roadway. Comparing the calculation results of COMSOL simulation with those of the Kaiser effect, the deviation rates of the three-direction principal stress σ_1 , σ_2 , and σ_3 are 4.42%, 3.92%, and 3.63%, respectively. This comparison verifies the accuracy of the calculation results of *in situ* stress based on the Kaiser effect in this study.

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References

- Alkan H, Cinar Y, Pusch G (2007). Rock salt dilatancy boundary from combined acoustic emission and triaxial compression tests. *Int J Rock Mech Min Sci*, 44(1): 108–119
- Bai X, Zhang D M, Wang H, Li S J, Rao Z (2018). A novel *in situ* stress measurement method based on acoustic emission Kaiser effect: a theoretical and experimental study. *R Soc Open Sci*, 5(10): 181263
- Basirat F, Tsang C F, Tatomir A, Guglielmi Y, Dobson P, Cook P, Dessirier B, Juhlin C, Niemi A (2021). Hydraulic modeling of induced and propagated fractures: analysis of flow and pressure data from hydromechanical experiments in the COSC-1 deep borehole in crystalline rock near Åre, Sweden. *Water Resour Res*, 57(11): e2020WR029484
- Cao Z Z, Wang Y, Lin H X, Sun Q, Wu X G, Yang X S (2022). Hydraulic fracturing mechanism of rock mass under stress-damage-seepage coupling effect. *Geofluids*, 2022: 5241708
- Chen Y L, Meng Q B, Li Y C, Pu H, Zhang K (2020). Assessment of appropriate experimental parameters for studying the Kaiser effect of rock. *Appl Sci (Basel)*, 10(20): 7324–7338
- Chen Y L, Ni J, Shao W, Azzam R (2012). Experimental study on the influence of temperature on the mechanical properties of granite under uniaxial compression and fatigue loading. *Int J Rock Mech Min Sci*, 56: 62–66
- Damani A, Sondergeld C H, Rai C S (2018). Experimental investigation of *in situ* and injection fluid effect on hydraulic fracture mechanism using acoustic emission in Tennessee sandstone. *J Petrol Sci Eng*, 171(7): 315–324
- Ganne P, Vervoort A, Wevers M (2007). Quantification of pre-peak brittle damage: correlation between acoustic emission and observed micro-fracturing. *Int J Rock Mech Min Sci*, 44(5): 720–729
- He Q Y, Li Y C, She S (2019). Mechanical properties of basalt specimens under combined compression and shear loading at low strain rates. *Rock Mech Rock Eng*, 52(10): 4101–4112
- Heimisson E R, Einarsson P, Sigmundsson F, Brandsdottir B (2015). Kilometer-scale Kaiser effect identified in Krafla volcano, Iceland. *Geophys Res Lett*, 42(19): 7958–7965
- Jiang Q A, Feng X T, Xiang T B, Su G S (2010). Rock burst characteristics and numerical simulation based on a new energy index: a case study of a tunnel at 2500 m depth. *Bull Eng Geol Environ*, 69(3): 381–388
- Jin Y, Qi Z L, Chen M A, Zhang G Q, Xu G Q (2009). Time-sensitivity of the Kaiser effect of acoustic emission in limestone and its application to measurements of *in-situ* stress. *Petrol Sci*, 6(2): 176–180
- Krietsch H, Gischig V, Evans K, Doetsch J, Dutler N O, Valley B, Amann F (2019). Stress measurements for an *in situ* stimulation experiment in crystalline rock: integration of induced seismicity, stress relief and hydraulic methods. *Rock Mech Rock Eng*, 52(2): 517–542
- Lai C Y, Wong L, Wallace M (2019). Review and assessment of in-situ rock stress in Hong Kong for territory-wide geological domains and depth profiling. *Eng Geol*, 248: 267–282
- Lavrov A (2003). The Kaiser effect in rocks: principles and stress estimation techniques. *Int J Rock Mech Min Sci*, 40(2): 151–171
- Li D X, Wang E Y, Kong X G, Jia H S, Wang D M, Muhammad A (2019a). Damage precursor of construction rocks under uniaxial cyclic loading tests analyzed by acoustic emission. *Constr Build Mater*, 206(10): 169–178
- Li X B, Chen J Z, Ma C D, Huang L Q, Li C J, Zhang J, Zhao Y Z (2022). A novel *in-situ* stress measurement method incorporating non-oriented core ground re-orientation and acoustic emission: a case study of a deep borehole. *Int J Rock Mech Min Sci*, 152(5): 105079
- Li Y C, Sun S Y, Tang C A (2019b). Analytical prediction of the shear behaviour of rock joints with quantified waviness and unevenness through wavelet analysis. *Rock Mech Rock Eng*, 52(10): 3645–3657
- Li Y H, Yang Y J, Liu J P, Zhao X D (2010). Experimental and theoretical analysis on the procedure for estimating geo-stresses by the Kaiser effect. *Int J Miner Metall Mater*, 17(5): 514–518
- Liu D, Fan J C, Wu S N (2018). Acoustic wave-based method of locating tubing leakage for offshore gas wells. *Energies*, 11(12): 3454–3474
- Liu G F, Feng X T, Jiang Q, Yao Z B, Li S J (2017). *In situ* observation of spalling process of intact rock mass at large cavern excavation. *Eng Geol*, 226: 52–69
- Liu X H, Dai F, Zhang R, Liu J F (2015). Static and dynamic uniaxial compression tests on coal rock considering the bedding directivity. *Environ Earth Sci*, 73(10): 5933–5949
- Lu J, Yin G Z, Zhang D M, Gao H, Li C B, Li M H (2020). True triaxial strength and failure characteristics of cubic coal and sandstone under different loading paths. *Int J Rock Mech Min Sci*, 135(11): 104439
- Meng Q B, Chen Y L, Zhang M W, Han L J, Pu H, Liu J F (2019). On the Kaiser effect of rock under cyclic loading and unloading conditions: insights from acoustic emission monitoring. *Energies*, 12(17): 3255–3272
- Miao S J, Cai M F, Guo Q F, Huang Z J (2016). Rock burst prediction

- based on *in-situ* stress and energy accumulation theory. *Int J Rock Mech Min Sci*, 83: 86–94
- Nian T, Wang G W, Xiao C W, Zhou L, Deng L, Li R J (2016). The *in situ* stress determination from borehole image logs in the Kuqa depression. *J Nat Gas Sci Eng*, 34(2): 1077–1084
- Panteleev I A, Mubassarova V A, Zaitsev A V, Shevtsov N I, Kovalenko Y F, Karev V I (2020). Kaiser effect in sandstone in polyaxial compression with multistage rotation of an assigned stress ellipsoid. *J Min Sci*, 56(3): 370–377
- Radwan A E, Abdelghany W K, Elkhawaga M A (2021). Present-day *in-situ* stresses in Southern Gulf of Suez, Egypt: insights for stress rotation in an extensional rift basin. *J Struct Geol*, 147: 104334
- Sabanov S (2018). Comparison of unconfined compressive strengths and acoustic emissions of Estonian oil shale and brittle rocks. *Oil Shale*, 35(1): 26–38
- Sause M, Schmitt S, Hoeck B, Monden A (2019). Acoustic emission based prediction of local stress exposure. *Compos Sci Technol*, 173: 90–98
- Schubnel A, Thompson B D, Fortin J, Gueguen Y, Young R P (2007). Fluid - induced rupture experiment on Fontainebleau sandstone: premonitory activity, rupture propagation, and aftershocks. *Geophys Res Lett*, 34(19): L19307
- Subrahmanyam D S (2019). Evaluation of hydraulic fracturing and overcoring methods to determine and compare the *in situ* stress parameters in porous rock mass. *Geotech Geol Eng*, 37(6): 4777–4787
- Tham L G, Liu H, Tang C A, Lee P, Tsui Y (2005). On tension failure of 2-d rock specimens and associated acoustic emission. *Rock Mech Rock Eng*, 38(1): 1–19
- Wu Y Q, Li S L, Wang D W, Zhao G H (2019). Damage monitoring of masonry structure under *in-situ* uniaxial compression test using acoustic emission parameters. *Constr Build Mater*, 215: 812–822
- Xiao W J, Yu G, Li H T, Zhan W Y, Zhang D M (2021). Experimental study on the failure process of sandstone subjected to cyclic loading and unloading after high temperature treatment. *Eng Geol*, 293: 106305
- Xie H P, Ju Y, Ren S H, Gao F, Liu J Z, Zhu Y (2019). Theoretical and technological exploration of deep *in situ* fluidized coal mining. *Front Energy*, 13(4): 603–611
- Ye C, Zhang D M, Zhou X, Wang X L, Yang H (2021). Reconstruction and sampling analysis of parent fracture group in underground mining. *Rock Mech Rock Eng*, 54(12): 6155–6172
- Yin G Z, Jiang C B, Wang J G, Xu J (2015). Geomechanical and flow properties of coal from loading axial stress and unloading confining pressure tests. *Int J Rock Mech Min Sci*, 76: 155–161
- Yin G Z, Jiang C B, Xu J, Guo L S, Peng S J, Li W P (2012). An experimental study on the effects of water content on coalbed gas permeability in ground stress fields. *Transp Porous Media*, 94(1): 87–99
- Yokoyama T, Sano O, Hirata A, Ogawa K, Nakayama Y, Ishida T, Mizuta Y (2014). Development of borehole-jack fracturing technique for *in situ* stress measurement. *Int J Rock Mech Min Sci*, 67: 9–19
- Yu X Y, Mao X W (2020). A preliminary discrimination model of a deep mining landslide and its application in the Guanwen coal mine. *Bull Eng Geol Environ*, 79(1): 485–493
- Zhang D, Yang Y, Wang H, Bai X, Ye C, Li S (2018). Experimental study on permeability characteristics of gas-containing raw coal under different stress conditions. *R Soc Open Sci*, 5(7): 180558
- Zhang G Q, Chen M (2010). Study of influence of Kaiser sampling deviation on underground stress measurements. *Energy Sources A Recovery Util Environ Effects*, 32(10): 886–893
- Zhang H H, Wang J X, Fan C J, Bi H J, Chen L, Xu C Y (2022). An improved coupled modeling method for coalbed methane extraction after hydraulic fracturing. *Geofluids*, 2022: 8895347
- Zhang S K, Yin S D (2014). Determination of *in situ* stresses and elastic parameters from hydraulic fracturing tests by geomechanics modeling and soft computing. *J Petrol Sci Eng*, 124: 484–492
- Zhao K, Gu S J, Yan Y J, Zhou K P, Li Q, Zhu S T (2018). A simple and accurate interpretation method of *in situ* stress measurement based on rock kaiser effect and its application. *Geofluids*, 2018: 9463439
- Zhao X G, Wang J, Qin X H, Cai M, Su R, He J G, Zong Z H, Ma L K, Ji R L, Zhang M, Zhang S, Yun L, Chen Q C, Niu L, An Q M (2015). *In-situ* stress measurements and regional stress field assessment in the Xinjiang candidate area for China's HLW disposal. *Eng Geol*, 197: 42–56
- Zhu J B, Zhou T, Liao Z Y, Sun L, Li X B, Chen R (2018). Replication of internal defects and investigation of mechanical and fracture behaviour of rock using 3D printing and 3D numerical methods in combination with X-ray computerized tomography. *Int J Rock Mech Min Sci*, 106: 198–212

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