Microseismic moment tensor based analysis of rock mass failure mechanism surrounding an underground powerhouse

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\textbf{ABSTRACT}

The failure mechanism of surrounding rock is an important issue in the field of underground engineering. To quantitatively understand the failure process and failure mechanism of the surrounding rock mass in deep underground engineering, the underground powerhouse of the Houziyan hydropower station was selected as a case study. The study area was determined by analysing the spatiotemporal distribution of microseismic (MS) events and site investigations. After noise reduction, P-wave arrival time extraction and positioning of MS signals, the moment tensor inversion method was used to determine the failure mechanism and fracture direction of the surrounding rock mass. The results showed that (1) the failure processes and mechanism of the surrounding rock mass can be effectively analysed through MS monitoring with moment tensor analysis and (2) the failure type of the surrounding rock mass downstream of the main powerhouse was characterized by shear failure. The stress state in this region was a strike-slip stress state. (3) The failure type of the surrounding rock mass at the arch roof of the main transformer chamber was characterized by tensile failure. The tensile stress of the intermediate stress axis was obvious, and the tectonic stress presented a state of near uniaxial compression-biaxial tension.

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\section{1. Introduction}

Numerous hydropower stations have been or are being constructed in Southwest China. Under complex engineering-geological conditions, especially in environments with great buried depths and high ground stress, excavation changes the initial in situ stress and energy state of the rock mass, which causes various types of engineering rock mass instability and failure (such as collapse, rock burst and fault slip) and severely affects the project schedule and safety (Feng et al. 2012; Ma et al. 2021).
Therefore, how to correctly identify and delineate the potential instability area and forecast in advance has become an important and difficult issue in hydropower station construction. As a three-dimensional real-time monitoring method, MS monitoring can record and track the initiation, development and expansion trend of rock microfractures in deep rock masses under construction and other stress disturbances in real time from the perspective of three-dimensional space, which effectively identifies and delineates the zone of rock microfractures and the gradually formed seismic nucleation risk areas. It provides guidance in the stability evaluation and analysis of engineering rock masses. This technology has been widely used in mining engineering (Li et al. 2007; Feng et al. 2017; Barthwal and Baan 2020), oil mining (Soma and Rutledge 2013; Ma et al. 2017; B. Zhang et al. 2019), slope engineering (Dai et al. 2017; B. Li et al. 2018), deep tunnels (Hirata et al. 2007; Liang et al. 2020; Xue et al. 2020), and underground powerhouses (Cai et al. 2001; A. Li et al. 2018; Li et al. 2020). Research fields of rock mass damage analysis show that many MS events are induced during the incubation, development and expansion of rock mass failure. Also, the seismic events have the characteristics of clusters in space, and the cluster zone of MS events contains plentiful rock fracture information (Ma et al. 2018; Woodward et al. 2018). Therefore, studying the MS events that are closely related to the failure of the surrounding rock, to a certain extent, reveals the internal formation mechanism. Through the analysis of event source mechanisms, we can deepen the understanding of rock mass failure and its relationship with the geological structure. The common methods for determining the source mechanism include inferred techniques, initial dynamic polarity inversion and waveform inversion.

Based on the assumption that sources with identical source mechanisms have similar distribution rules of source parameters, the discontinuity inference method can infer the rock mass fracture mechanism of the event group by analysing the temporal and spatial evolution trends of many event clusters. Mollison et al. (2003) deduced the event focal mechanism near the geological structure by comprehensively considering the spatial distribution of geological structure and MS event clusters; moreover, the ratio of S- to P-wave energy can also be used for quantitative analysis of focal mechanisms (Cai et al. 1998, 2001). Because discontinuous inference requires many events to be used, these techniques may give ambiguous results if there are multiple mechanisms in the event population. Focal mechanism solutions from the first motion polarities determine the failure mechanism of the source by observing the first motion polarity of the P wave. However, for the analysis of fracture characteristics of the engineering rock mass, the inversion results may deviate because of the uneven distribution or the limited number of stations. At the same time, the focal mechanism has many non-double couple source mechanisms, which is inconsistent with the hypothesis of initial dynamic polarity and may give ambiguous results.

Moments tensor inversion is a theory widely used in the field of geophysics to analyse natural earthquakes. The results obtained by moment tensor inversion are more widely applicable than those obtained by other methods of information. Gilbert et al. (Gilbert 1971) first introduced moment tensor theory and regarded it as a complete description of the first order. Aki et al. (Nolet 1981) discussed the acquisition method of source waves and the waveform analysis method and obtained the moment tensor...
solution. Ohtsu et al. (Ohtsu 1991) proposed the generalized acoustic emission theory based on elastodynamics and gave the concrete expression method of the moment tensor. With the continuous development of rock mechanics, research on the rock internal fracture mechanism is gradually in-depth. To obtain the internal damage evolution process and law of rock crack initiation, propagation, penetration and interaction and the corresponding relationship with stress, researchers have started to study the source mechanism of internal rock fracture in engineering rock masses using the moment tensor method. Grosse et al. (Grosse and Finck 2006) conducted a series of indoor acoustic emission experiments to verify the accuracy of the moment tensor inversion results of the rock fracture mechanism. Baker et al. (Baker and Young 1997) studied the source mechanism of a single source event, and the results showed that there would be tension-shear and contraction-shear mechanisms in the source excitation process. Feigner et al. (Feignier and Paul Young 1992) analysed the fracture mechanism of a tunnel rock mass by the ratio of the volume component to the shear component. Zhao et al. (2018, 2019) systematically analysed the potential seepage channels in mining and combined the inversion results with numerical simulation to further analyse the rock mass stability based on considering rock mass damage. Ming et al. (2013) analyzed the risk and formation mechanism of rock blast in deep-buried tunnels and further systematically analysed the fracture surface distribution characteristics of rock mass instability at the site.

The combination of MS technology and the moment tensor not only obtains the spatiotemporal evolution mechanism of rock fracture but also describes the fracture type and direction of the source in detail. The rock mass mechanics of underground powerhouses are volatile because of the influence of many factors, such as large variations in buried depth, intensive layout, complex geological conditions and geological structure, and uncertainties in rock strength and deformation. Furthermore, it is very difficult to locate the source, retrieve the moment tensor and determine the source parameters. Therefore, few reports are available on using the moment tensor of MS events in underground powerhouses to study the focal mechanism of microfractures. Based on the above considerations, the underground powerhouse of the Houziyan hydropower station is selected as the test site for in-depth study.

In this paper, MS monitoring, moment tensor inversion and iterative joint inversion are combined to study the focal mechanism and stress field changes in the damaged area of underground powerhouse. Firstly, the potential instability areas of underground caverns in different periods are identified and delineated by using geological survey and MS analysis. Then, the optimized moment tensor inversion method for large underground caverns is applied to analyze the MS events, and multiple discriminant indexes are used to solve the source parameters, so as to summarize and analyze the preparation process of MS events. Finally, the change of stress field in the damaged area is obtained by using the iterative joint inversion method, and the evolution process of focal mechanism and the change law of stress field in the damaged area of underground powerhouse are mainly discussed.
2. Study area

2.1. Engineering background

The Houziyan hydropower station is located on the Dadu River in Sichuan Province, China (see Figure 1). The underground powerhouse is primarily composed of the main powerhouse, the main transformer chamber, tailrace surge chambers and two tailrace tunnels, among which the main powerhouse and main transformer chamber are arranged in parallel with a dip direction of N61°W (see Figure 2). The dimensions of the main caverns include the main powerhouse, the main transformer chamber and the tailrace surge chamber, which are 219.5 m × 29.2 m × 68.7 m, 139 m × 18.80 m × 25.2 m, and 140.5 m × 23.5 m × 75.0 m, respectively. The entire cavern system is a typical underground rock engineering project with a large span, high sidewalls and complicated excavation processes under complex geological environments.

The Houziyan underground powerhouse group is in very complex geological conditions that are rarely encountered in hydropower projects. It is located in a region of high ground stress, with relatively low surrounding rock strength and severe brittle failure of the rock mass. Based on the in situ stress measurement using the hydraulic
fracturing described in Dai et al. (2015), the maximum principal stress is approximately 21.46–36.43 MPa, and the most principal stress direction of regional tectonic stress is the EW direction, which is parallel to the direction of the main powerhouse. The rock mass is primarily hard and completely metamorphic limestone, which tends to store high strain energy. Hence, these conditions present multiple hazards: the deformation and failure of the surrounding rock are prominent. In some areas, slight-moderate rock bursts occurred during the excavation of the underground powerhouse.

2.2. MS monitoring system

To reveal the excavation-induced damage evolution regularities of the surrounding rock mass and offer early warning of rock failure, a high-precision MS monitoring system produced by the ESG (Engineering Seismology Group) Company of Canada was adopted in the underground caverns of the Houziyan hydropower station on April 12, 2013. The ESG MS monitoring system primarily consists of a Paladin signal acquisition system, Hyperion digital signal processing system, and accelerometer sensors. The frequency response of the acceleration sensors ranged from 50 Hz to 5000 Hz, and the sensitivity was 30 V/g. The sampling frequency of the Paladin signal acquisition system is 10 kHz. Each sensor receives the elastic wave signal released by rock fracture and transmits it to the Paladin data acquisition substation through cable. The ratio of the short-term average and long-term average (STA/LTA) is used to calculate the arrival time of elastic waves with a triggering value. When the number of signals exceeds the set threshold value, it is recognized as an effective event, and the data are transmitted to the Hyperion signal data processing host for storage. On this basis, a wireless data transmission system is constructed for timely subsequent signal processing and analysis. More details about this engineering project and the ESG MS monitoring system were documented in Li et al. (2019).
3. Methodology

3.1. MS signal denoising

The noise made by engineering activities and background noise dramatically interferes with the interpretation and analysis of MS signals. It is evident that signal denoising is necessary before moment tensor inversion. Because of the randomness and nonstationary nature of MS signals, traditional noise elimination filtering methods (such as Fourier noise elimination) can suppress noise to a certain extent, but they are primarily effective for periodic stationary signals, while their effects on nonstationary signals containing spikes or abrupt changes are not good. Empirical mode decomposition (EMD) is a powerful tool for processing seismic signals in geosciences and can treat random nonstationary signals well (Huang et al. 1998). Compared with the wavelet transform and other time-domain analysis methods, the EMD method has many advantages. For example, it does not need to preset the basis function and decomposes the signal into IMFs of different scales based on the characteristics of the signal itself. However, some inherent shortcomings may impose negative influences on the results (H. Li et al. 2017), such as the modal aliasing phenomenon. Later, EEMD was proposed to use white noise of different time scales to compensate for the missing frequency band (J. Zhang et al. 2019). Finally, the original signals can be expressed by Eq. (1):
where \( x(n) \) is the MS signal recorded by the ESG MS monitoring system. \( IMF_i \) is the \( i \)th intrinsic mode function. \( r_k(n) \) is a residual component, and \( k \) is the final number of decomposition layers. In this study, a simple filtered MS signal was obtained using the Butterworth filter and the removal trend line of ESG WaveVis software. The simple filtered MS signal was decomposed into a series of IMF components from high frequency to low frequency by EEMD. Then, the simple filtered signal is decomposed by EEMD into a series of IMFs. The correlation coefficient between each signal component and the original signal is calculated as follows:

\[
\rho_{IMF_i, x(n)} = \frac{\text{Cov}(IMF_i, x(n))}{\sqrt{D(IMF_i)} \cdot \sqrt{D(x(n))}}
\]

where \( \text{Cov}(IMF_i, x(n)) \) is the covariance of the IMF and \( x(n) \), and \( D(IMF_i), D(x(n)) \) are the variances of the IMF and \( x(n) \), respectively. The correlation coefficients were arranged according to the sequence of the IMF, the position of the first extremal point in the correlation coefficient sequence was determined as the position of the boundary component, and all the high-frequency components before that position were removed. Reconstruct the remaining part to form the signal after noise reduction. The filtered waveform is shown in Figure 3. The denoised waveform greatly reduces the high-frequency noise in the time domain (Figure 3a). By analyzing Figure 3(b), for the sake of clarity, some signals in the dotted yellow box are amplified. The high-frequency noise is eliminated very well, almost no residual, and there is no frequency domain truncation phenomenon at the boundary between the frequency band range of the MS signal and the frequency band range of the noise, which makes the denoised result closer to the MS signal in the time domain waveform. Noise reduction processing can effectively improve the quality of the collected MS signal waveform, which is conducive to the subsequent inversion analysis.

### 3.2. Automatic time-picking of the first arrivals

In addition to the detailed denoising MS signal, the emphasis is on the location principles and mechanics. The accuracy of the location of the MS event is more susceptible to the time picking of the first arrivals. Moreover, the signals after filtering contain substantial information on rock mass failure; therefore, after signal denoising, the arrival time picking turned out to be essential. Currently, the short- and long-term average (STA/LTA) ratio picker (Allen 1978; Li et al. 2016; Mborah and Ge 2018) and the autoregression model and Akaike information criterion (AR-AIC) method (Akaike 1974; X. Li et al. 2017) are the two most widely used approaches for picking seismic signals in which prior waveforms are always unknown. In this study, the STA/LTA-AIC method is selected for determining the P-phase arrival. The ratio of STA/LTA and the characteristic function can be defined in the following function:
$$R(t) = \frac{STA(t)}{LTA(t)} = \frac{STA(t-1) + \frac{1}{n} [CF(t) - STA(t-1)]}{LTA(t-1) + \frac{1}{m} [CF(t) - LTA(t-1)]}$$

(3)

$$CF(t) = Y(t)^2 - Y(t-1) \cdot Y(t+1)$$

(4)

where \(n\) and \(m\) are the lengths of the short window and long window, respectively. \(CF(t)\) is the characteristic function of the term, which varies according to the MS data.

Before the P-wave onset time, STA and LTA measure the mean background noise value, so STA/LTA is close to 1. When the P wave arrives, the STA is more sensitive to rapid increases in the amplitude of the CF, whereas the LTA measures the local background amplitude. Therefore, if the ratio exceeds the predetermined threshold, a phase arrival can be declared. After the approximate arrival time \(k\) of the P wave was obtained by STA/LTA, the AIC method was adopted to further search its time range to determine the accurate arrival time of the P wave to ensure the accuracy of MS time positioning and moment tensor inversion. The AIC method for the signal \(x(t)\) \((t = 1, 2, 3 \ldots, L)\) can be defined in the following function (see Eq. (5)).
\[
AIC(k) = k \cdot \log \{ \text{var}(x[1, k]) \} - (L - k - 1) \cdot \log \{ \text{var}(x[k + 1, L]) \}
\]

(5)

The arrival time of the MS signal was extracted using the STA/LTA-AIC method, and the MS event was located by the simplex algorithm during the P-arrival time (see Figure 4).

Uniaxial acceleration sensors are used in the Houziyan hydropower station MS monitoring system, and the average sensitivity of the sensors is 30 V/g. Considering the MS signal captured by a sensor is the acceleration signal, the displacement curve of the measuring point can be obtained by integrating the time twice by the MS signal. The displacement value of the P wave of the initial MS was extracted by the P-arrival time.

3.3. Inversion of the moment tensor

The spatial distribution of source locations can therefore be used to infer the fracture geometry and network complexity, whereas the corresponding moment tensor solutions provide information about the source mechanisms and stress orientations.

In MS monitoring, the MS signal contains abundant rock fracture source information, and different fracture characteristics have different spectrogram characteristics. An improved understanding of the physical processes governing induced seismicity is important for maximizing production and reducing seismic hazards. Seismic source mechanisms can provide insights into the fracturing behaviour of the reservoir and surrounding rocks and an understanding of the evolution of the stress field. These insights can contribute to advanced knowledge of the fracture type, propagation, and connectivity. Based on the far-field approximation, synchronous source approximation and false pulse source time function, the \(k\)th component of the displacement \(U\), recorded at position \(x\) and time \(t\), is mathematically presented as follows:

\[
U = GM
\]

(6)

where \(U\) is the recorded data (displacements), \(M\) is the model vector (6 moment tensor components) and \(G\) are the Green’s functions. This system of equations can be solved by the least squares (LS) technique, either in time or in the frequency domain. The matrix-vector notation of Eq. (6) is mathematically presented as follows:

\[
\begin{bmatrix}
    u_1 \\
    u_2 \\
    \vdots \\
    u_N
\end{bmatrix} =
\begin{bmatrix}
    G_{1,1}^1 & G_{2,2}^1 & G_{3,3}^1 & G_{2,3}^1 + G_{3,2}^1 & G_{1,3}^1 + G_{3,1}^1 & G_{1,2}^1 + G_{2,1}^1 \\
    G_{1,1}^2 & G_{2,2}^2 & G_{3,3}^2 & G_{2,3}^2 + G_{3,2}^2 & G_{1,3}^2 + G_{3,1}^2 & G_{1,2}^2 + G_{2,1}^2 \\
    \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\
    G_{1,1}^N & G_{2,2}^N & G_{3,3}^N & G_{2,3}^N + G_{3,2}^N & G_{1,3}^N + G_{3,1}^N & G_{1,2}^N + G_{2,1}^N
\end{bmatrix}
\begin{bmatrix}
    M_{11} \\
    M_{22} \\
    M_{33} \\
    M_{23} \\
    M_{13} \\
    M_{12}
\end{bmatrix}
\]

(7)

However, in the underground powerhouse, because of cost considerations, most of the sensors used in large underground caverns are still uniaxial sensors, making \(U\) in Eq. (7) difficult to obtain. Based on experimental acoustic emission tests, Ohstu et al.
(1991) proposed that the point source approximation is valid when the wavelength is far greater than the source radius or the sensors are relatively far away. Compared with that of the earthquake, the distance between the source point and the sensor MS monitoring system is small. Therefore, the arrival times of the P and S waves of the MS signal are not much different, which means that the P and S waves in the MS signal have a large overlap. Therefore, the components of the P wave are relatively clean, so the far-field data of the P wave are used to invert the moment tensor in the wave-form. When only the P-wave far-field term in the solution of Lamb is considered, it can be reduced to a time-independent constant tensor, mathematically presented as follows:

\[ u_i = \frac{\gamma_{ij} \gamma_{ik}}{4\pi \rho v_p^3 R} M_{ij} \]  

where \( u_i \) is the first move along the \( i \)-axis and \( R \) is the absolute distance between the receiving point and the source point. \( \gamma_i = (x_i - \xi_i)/R \), among them, \( x_i, \xi_i \) are the three-dimensional coordinates of sensor and MS event, respectively.

The moment tensor cannot directly reflect the failure types and characteristics of the rock mass, so the physical correspondence between the source moment tensor and the source rupture essence can be obtained by reasonable decomposition of the moment tensor. In the case of identical moment tensor results, different decomposition methods of the moment tensor may result in different fractures. Therefore, the most crucial step in the study of rock fracture types is reasonably decomposing the moment tensor. The most widely adopted moment tensor decomposition method was proposed by Randall (Feignier and Paul Young 1992). The resolved moment tensor matrix can be divided into three components: the isotropic (ISO) component, (DC) component and compensated linear vector dipole (CLVD) component according to the following equation:

\[
M = M_{ISO} + M_{DC} + M_{CLVD}
\]

\[
= \frac{1}{3} (M_1 + M_2 + M_3) \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} + \frac{1}{2} (M_1 - M_3) \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & -1 \end{bmatrix} + \frac{1}{6} (2M_2 - M_3 - M_1) \begin{bmatrix} -1 & 0 & 0 \\ 0 & 2 & 0 \\ 0 & 0 & -1 \end{bmatrix}
\]  

where \( M, M_2, \) and \( M_3 \) are the eigenvalues of the moment tensor, which obey the relationship \( M_1 > M_2 > M_3 \); \( M_{DC} \) corresponds to changes in the volume in the seismic source region; and \( M_{CLVD} \) corresponds to shear displacements.
3.4. Identification of rock fracture type

After decomposing the solved moment tensor, establishing the relationship between the moment tensor and the type of rock mass fracture is vital. According to the results of the moment tensor, two methods are used to discriminate the types of rock failures: the moment tensor decomposition discriminant method and the angle of motion method.

For the determination of the rock fracture surface under a certain stress state, different failure criteria may result in different results. At the same time, there are certain differences between rock parameters and rock mass parameters, and rock failure criteria are mostly used in numerical simulations. The application of analysis based on MS information will complicate the problem. Therefore, this paper first adopts the method given by Aki and Richard to calculate the moment tensor from the fracture surface position, the motion direction vector in an isotropic medium and the fracture surface normal vector. The relationship between the movement direction vector and the moment tensor eigenvalue vector is derived, and the result of the rock fracture surface orientation based on the MS information is derived.

According to the moment tensor inversion, we can determine the physical quantities related to the geometric properties and motion properties of the fault plane, such as the normal and motion vectors of focal planes. In an isotropic elastic medium, after diagonalizing the moment tensor of the MS source, in the principal axis coordinate system, it can be expressed as (Vavryčuk 2015):

\[
M = \begin{bmatrix}
M_1 & 0 & 0 \\
0 & M_2 & 0 \\
0 & 0 & M_3
\end{bmatrix} = uS \begin{bmatrix}
(\lambda + \mu)\hat{n} \cdot \hat{v} + \mu & 0 & 0 \\
0 & \lambda\hat{n} \cdot \hat{v} & 0 \\
0 & 0 & (\lambda + \mu)\hat{n} \cdot \hat{v} - \mu
\end{bmatrix}
\]  

(10)

where \( u \) is the displacement in the direction of motion of the fracture surface, \( S \) is the surface area of the fracture, \( \lambda \) and \( \mu \) are the Lame constants, and \( \hat{v}, \hat{n} \) are the motor direction and normal direction of the fracture surface, respectively.

Based on the symmetry of the moment tensor and the relationship between the eigenvalues of the moment tensor, the eigenvector can be expressed as

\[
\vec{e}_1 = \frac{\vec{n} + \vec{v}}{|\vec{n} + \vec{v}|} \quad \vec{e}_2 = \frac{\vec{n} \otimes \vec{v}}{|\vec{n} \otimes \vec{v}|} \quad \vec{e}_3 = \frac{\vec{n} - \vec{v}}{|\vec{n} - \vec{v}|}
\]  

(11)

where \( \vec{e}_1, \vec{e}_2, \) and \( \vec{e}_3 \) are the eigenvectors corresponding to the eigenvalues \([M_1; M_2; M_3]\) of the moment tensor. The corresponding relationship is \( \vec{e}_1 \perp \vec{e}_2 \perp \vec{e}_3 \). The angle between the vectors \( \vec{v} \) and \( \vec{n} \) is assumed to be \( \beta \). According to Eq. (10), the following equation can be obtained:
\[ \vec{n} \cdot \vec{v} = \cos \beta = \frac{M_1 + M_3 - 2M_2}{M_1 - M_3} \]  

(12)

It can be deduced that the movement direction and normal direction of the fracture surface should be:

\[ \vec{n} = \cos \frac{\beta}{2} \vec{e}_1 + \sin \frac{\beta}{2} \vec{e}_3 = \sqrt{\frac{M_1 - M_2}{M_1 - M_3}} \vec{e}_1 + \sqrt{\frac{M_2 - M_3}{M_1 - M_3}} \vec{e}_3 \]  

(13)

\[ \vec{v} = \cos \frac{\beta}{2} \vec{e}_1 - \sin \frac{\beta}{2} \vec{e}_3 = \sqrt{\frac{M_1 - M_2}{M_1 - M_3}} \vec{e}_1 - \sqrt{\frac{M_2 - M_3}{M_1 - M_3}} \vec{e}_3 \]  

(14)

According to the normal direction of the fracture surface, the geometric equation expression can be obtained, and then the azimuth and inclination angles of the fracture surface can be determined. In the terminology of the field, the two planes determined by these two vectors are called focal planes, one of which is the fault plane, and the other is called the auxiliary plane. In underground surrounding rocks, such as the caverns of hydropower stations, the direction of movement of the fault plane and the fault plane are often not coplanar. The angle of motion is defined as the angle between the direction of the motion vector and the fracture surface.

From the perspective of the displacement direction of the fracture surface caused by different fracture mechanisms, the shear fracture causes the fracture surface to be displaced along the slip angle \( \alpha \), while tensile fracture causes the fracture surface to be displaced (displacement) along the normal direction. Because of the existence of these two completely independent dislocation modes, the geometric parameters of the dislocation of the fracture surface can be used to determine the dominant form of fracture.

Based on determining the rock fracture surface and movement direction, Ouyang et al. (1992) used the angle between the movement direction and the fracture surface \( \alpha \) (as shown in Figure 5, select the rupture surface of a specific occurrence to express by the protruding angle \( \alpha \)) to judge the type of rock fracture, but they used a fixed fracture type identification index, and different rocks have different shear strengths under different stress conditions. Therefore, a fixed threshold cannot be used to determine the type of fracture. It varies according to the ground stress conditions, rock mechanics parameters and excavation conditions. For the source model, the angle of motion determines different failure mechanisms.

Because of the excavation of underground engineering, stress concentrations are formed, and the usual stress concentration coefficient is from 2 to 3, which means that the circumferential stress of the surrounding rock under the action of excavation unloading is generally 2 to 3-fold larger than the original stress concentration. Assuming that the maximum value of the two normal stresses in the in-situ stress field along the axis of the parallel tunnel is \( \sigma \), the circumferential stress of the rock mass of the surrounding rock is twice the stress concentration factor. According to the Mohr-Coulomb criterion, the shearing strength of the rock mass can be approximated based on the movement angle fracture type discriminant method proposed in
this study based on the intensity of rock mechanics parameters and stress conditions. 

\[ F_s = \sigma \cos \phi, \quad \text{and} \quad \phi \text{ is the angle of internal friction.} \]

For the explosive event, the dislocation is in the form of shear dislocation and tensile dislocation, while the corresponding dislocation angle identification standard is mathematically presented as follows (Ming et al. 2013):

\[ \tan \alpha > \frac{F_t}{F_s} \quad (15) \]

where under certain conditions of in situ stress, \( F_t \) and \( F_s \) are the tensile strength and shear strength of the rock mass, respectively.

For implosion events, the dislocation forms are shear dislocations and compression dislocations, while the corresponding dislocation angle identification standard is mathematically presented as follows (Ming et al. 2013):

\[ \tan \alpha < \frac{F_t}{F_s} \quad (16) \]
where under certain conditions of in situ stress, \( F_n \) and \( F_s \) are the compressive strength and shear strength of the rock mass, respectively.

In addition to the above motion-included angle discriminant method considering the tensile failure Mohr-Coulomb criterion, there are other classifications for the moment tensor decomposition discriminant method. According to the decomposition result of the moment tensor, the rupture type of the source event is judged, and the following criteria proposed by Feigner and Paul Young (1992) are used:

\[
R = \frac{\text{tr}(M)}{\left| \text{tr}(M) + \sum |m_i^s| \right|} \times 100
\]

where \( R \) is the ratio of the volume component to the shear component, \( \text{tr}(M) \) is the trace of the moment tensor, and \( m_i^s \) is the eigenvalue of the partial tensor. For the different results, there are the following criteria:

\[
\begin{align*}
R &> 30 & \text{Tension failure} \\
30 & \geq R \geq -30 & \text{Shear failure} \\
R &< -30 & \text{Compressive failure}
\end{align*}
\]

The relatively complex fracture mechanism of the surrounding rock of a large underground cavern may contain shear, tension, compression, implosion and other fracture mechanisms, and the stress situation is also relatively complex. Regardless of whether the ratio of the R-value or the angle of dislocation is used to determine the fracture mechanism, additional parameters are required. When the angle of motion \( \alpha \) is used as an indicator of the shear, tension or compression fracture mechanism, the shear strength of the rock mass is not maintained similarly across conditions. Therefore, fixed parameters cannot be used to determine the type of fracture but differ according to the stress conditions, rock mechanics parameters and excavation conditions.

At the same time, the source type diagram based on tensor parameters \( T \) and \( K \) has been widely used in the study of moment tensor source mechanism because it can show the rupture type of the source more intuitively, and can reflect the main rupture types of the sample and the source event in the engineering rock mass. As shown in Figure 5(b), parameter \( T \) represents the partial part of moment tensor, and its range is from \(-1\) from the positive compensated linear vector dipole (+CLVD) at \(+1\) to the pure negative compensated linear vector dipole (−CLVD) at \(+1\), and through the pure double couple (DC) at the origin. The parameter \( K \) represents the change of source volume and measures the isotropic component of moment tensor, which ranges from the uniform compression type at the bottom-1 to the uniform expansion type at the top \(+1\).

According to the content, based on the theory of the moment tensor, three characterizations of the rupture mechanism of moment tensor parameters can be obtained, namely, the angle of motion \( \alpha \) and \( R \) index for quantifying the fracture type, and based on the moment tensor component percentages of the Hudson source-type diagram, three parameters are calculated according to the results of the fault rupture
mechanism, focal mechanism solution of inversion of rock mass fracture, and fracture surface occurrence.

3.5. Stress redistribution

The focal mechanism solution of the source is the main way to understand the seismic fault and its rupture characteristics. At the same time, the focal mechanism solution also reflects the stress state in the event cluster, which lays a foundation for the study of the tectonic stress field. According to the two-force couple point source model, the focal mechanism solution of each source contains the bearing of P, B and Taxes and two node-plane parameter information. The P and T taxes of the focal mechanism solution represent the focal stress field but cannot represent the real tectonic stress field.

The relative motion of the two plates of the fault contains the information of shear stress on the fault plane. If tangential traction can be obtained by retrieving many fault planes in the region, we can infer the information of the regional stress field. Based on this theory, Michael et al. (Michael 1987) proposed a linear method for inversion of the stress field based on focal mechanism solution data. Vavryčuk et al. (Vavryčuk 2014) proposed an iterative joint inversion method (IJIM) based on the linear inversion method of Michael. In this method, the fault instability parameter I is added, and the surface with a large value of I is defined as the fault plane. In the iterative process, the fault plane is selected, which greatly improves the inversion accuracy. At the same time, stochastic noise can be added to repeat the inversion. Based on the IJIM, combined with in situ stress measurement, field investigation and field activity analysis, this paper inverts the stress field characteristics of the MS event gathering area of an underground powerhouse.

4. Results and discussion

4.1. Spatiotemporal distribution of source parameters

4.1.1. Source parameter characteristics of the MS cluster controlled by fault

From November 2013 to March 2014, the downstream sidewalls of the main powerhouse were under excavation. Because of intensive discontinuities distributed at the downstream sidewalls, surrounding rock mass failures frequently occurred. As of March 31, 2014, the main powerhouse was completed. The time distribution of MS events during this period is shown in Figure 6. The frequency of MS events during the excavation of the V~IX bench occurred to a certain extent from December 15, 2013, to January 15, 2014.

Figure 7 shows the front view and the side view of the spatial distribution of MS events in the underground powerhouse, where the size of the sphere represents the energy scales and different colours represent different moment magnitudes. After filtering out the noisy events, as seen in Figure 7, 116 MS events were identified in the excavation-disturbed areas over the selected period from Dec 15, 2013, to Jan 15, 2014. The MS events primarily accumulated in the downstream spandrel and sidewall between units 2 and 3 of the main powerhouse, which form a banded distribution
(the MS cluster will be referred to hereafter as event A for brevity). The MS events in this region were also of high energy and large magnitude, representing the main rock mass damage of the underground caverns.

Combined with the analysis of the on-site construction status, at this time, the main powerhouse was excavated at benches V and VI. Through the analysis of geological data, it was found that there were faults f1-1-3 and f1-1-5 in the region where the banded MS events were gathered. Combined with the geological conditions, the rock quality in this region was found to be relatively poor because of the existence of several weak structures. Therefore, it can be deduced that this surrounding rock mass deformation is primarily influenced by the excavation unloading-induced interior high-stress concentration in the fractured rock mass region.

This finding shows that the time gathering area of MS can reveal the relationship with mining activities and geological structures well. MS detection technology can

Figure 6. Temporal distribution of MS events.

Figure 7. Spatial distribution of MS events. (a) MS event elevation view, (b) MS density contour elevation view, (c) MS event vertical view, and (d) MS density contour vertical view.
identify and delineate the geological structure inside the surrounding rock of the factory building. By introducing the moment tensor method in geophysics, the fracture mechanism and the stability of the fracture surface of the MS event gathering area caused by the excavation and the geological structure can be analysed. In addition, it can describe in detail the type and direction of the rupture of the earthquake source, predict and warn of the dynamic disasters, such as those of underground engineering and mines caused by geological structures, and provide guidance and suggestions for the excavation and support of underground powerhouses.

4.1.2. Source parameter characteristics of the MS cluster controlled by excavation unloading intensity

From April to July 2014, the excavation of the main powerhouse was basically completed; at the same time, the main transformer room was subjected to secondary excavation, and the construction of the #4 bus tunnel was performed. The time distribution of MS events in this period is shown in Figure 8. Analysing the time evolution of MS events, the overall activity of MS events is relatively weak. Normally, there are fewer than 5 MS events per day. With the change in construction intensity, the number of MS events fluctuates. Among them, the relatively frequent MS event activities primarily occurred from June 11, 2014, to July 26, 2014. The engineering geological data show that there is no fault or weak structural surface in this area, which can be inferred to indicate that the accumulation of MS events is primarily controlled by the excavation unloading intensity of the underground cavern group.

After filtering out the noisy events, as seen in Figure 9, 121 MS events were identified in the excavation-disturbed areas during the selected period from Jun 11, 2014, to Jul 26, 2014 (this MS cluster will be referred to hereafter as event B for brevity). Compared with the field construction, it was found that MS activities were closely related to the overall construction status of the underground cavern. Although the excavation of the main powerhouse is basically completed, the secondary excavation of the main transformer room and the unloading of bus tunnel #4 have a greater effect on the MS activity in the area above the top arch.

The spatial distribution and temporal evolution characteristics of the MS events were studied. Combined with the results of conventional monitoring and field surveys, the macroscopic failure state of rock masses under different construction
conditions was revealed, and the surrounding rock damage area was delineated according to the law of rock fracture energy loss accumulation to lay the groundwork for the next analysis of the surrounding rock fracture damage mechanism.

4.2. Analysis of the fracture mechanism based on moment tensor inversion

To further determine the source model for these events and to represent the source mechanism differently according to ISO, DC, and CLVD components, a Hudson
source-type diagram was drawn. In the Hudson source-type diagram, the horizontal scale describes the type of the medium volume component of the source, and the parameters on the vertical scale describe the proportion of the volume change component. All the MS events in the two event clusters were solved, and the corresponding moment tensor was decomposed to draw the Hudson source-type diagram, as shown in Figure 10.

The MS events of event A are clustered around the centre of the source-type diagram, while a small number are clustered in the upper left corner of the source-type diagram, further indicating that these events may be related to shear rupture or fault slip and a few shear failures. During the monitoring period, shear failure is the main rock mass in the study area. Meanwhile, it can be concluded that the MS events of event B are related to tensile failure or crack opening because these events cluster in the upper left quadrant of the Hudson source-type diagram. The rock fracture in the MS event gathering area is primarily dominated by shear-tensile failure.

To analyse the source mechanism of MS events at corresponding locations, using the MTI method (as presented in Eqs. (6) and (7) into Eq. (9), the failure type and orientation of microcracks can be obtained, and in turn, the formation mechanism of the rock mass can be deduced. To ensure the reliability of the results, only those with moment magnitudes greater than 1.0, phase clarity and high signal-to-noise ratios are used, and 44 inversion results are obtained. Figures 11(a) and 12(a) show the moment tensor results of events A and B, respectively. Because of space limitations, we restricted the number of beachballs of their moment tensor. The basic information about the identification of fracture mechanisms of events A and B is listed in Tables 1 and 2, respectively.

Based on engineering geological reports, corresponding specific rock mechanics parameters are obtained, along with the rule of in situ stress conditions of rock failure mechanism analysis. The lithology of the downstream sidewalls of the main powerhouse and the dome roof of the main transformer room of Houziyan Hydropower Station is dolomitic limestone and metamorphic limestone. The surrounding rock is hard and intact, primarily with a thick to superthick layered structure and partially with a medium-thick layered structure. The rock mass of MS event
clusters is deemed class III by considering the stress discount. Geological data show that the fault is primarily distributed in the downstream sidewall area of the main powerhouse, so the rock mass in the fault area is reduced to class III2.

According to Sec. 3.4, the computed shear strengths of the downstream sidewall rock mass of the main powerhouse and the dome roof rock mass of the main transformer room are 29.85 MPa and 22.69 MPa, respectively. The conventional rock mechanics test on the surrounding rock of the underground powerhouse shows that the initial mobilized friction angles of the surrounding rocks of classes III1 and III2 are $38.66^\circ$ and $34.99^\circ$, respectively. At the same time, the uniaxial compressive strengths of the surrounding rocks of classes III1 and III2 are 100 MPa and 80 MPa, respectively. The tensile strength of the rock is generally $1/4 \sim 1/25$ of the compressive strength, with an average of 1/10. Therefore, a preliminary determination of the tensile strength of the surrounding rocks of the Houhouyan underground powerhouse obtains 10 MPa and 8 MPa, respectively; a general criterion for judging the fracture

Table 1. Resolved fault plane solutions and the preliminarily inferred source types.

| No. | Focal plane-1 | Focal plane-2 | R  | $\alpha$ | Tag          |
|-----|---------------|---------------|----|---------|--------------|
| 1   | 245.29        | 79.13         | 19.66 | −7.47   | Shear failure|
| 2   | 291.78        | 11.58         | −7.92 | 1.82    | Shear failure|
| 3   | 223.84        | 82.87         | 6.38  | 2.19    | Shear failure|
| 4   | 333.32        | 34.14         | 28.04 | 45.13   | Shear/Tensional failure|
| 5   | 269.59        | 50.79         | −19.34| 40.61   | Shear/Tensional failure|
| 6   | 343.5         | 33.57         | −31.36| 7.85    | Compressional failure|
| 7   | 180.55        | 16.28         | 10.44 | −20.08  | Shear failure|
| 8   | 358.56        | 34.14         | 23.28 | 19.93   | Shear failure|
| 9   | 328.84        | 86.06         | −18.39| 25.27   | Shear/Tensional failure|
| 10  | 102.60        | 79.13         | 19.66 | −7.47   | Shear failure|
| 11  | 272.46        | 88.61         | −11.31| 12.95   | Shear failure|
| 12  | 256.52        | 78.36         | −14.19| −0.07   | Shear failure|
| 13  | 355.48        | 16.09         | −26.53| 16.79   | Shear failure|
| 14  | 341.12        | 50.38         | −25.94| −27.83  | Compressional failure|

Figure 12. Mechanisms of the selected Event B MS data. The two central pictures are the positions of the MS events under different views.
mechanism, such as Eq. (19), can be obtained.

\[
\begin{align*}
\text{Event A} & \quad \left\{ \begin{array}{l}
\alpha \in (19.42^\circ, 90^\circ) \quad \text{tensile failure} \\
\alpha \in [-74.16^\circ, 19.42^\circ) \quad \text{shear failure} \\
\alpha \in [-90^\circ, -74.16^\circ) \quad \text{compressive failure}
\end{array} \right. \\
\text{Event B} & \quad \left\{ \begin{array}{l}
\alpha \in (18.52^\circ, 90^\circ) \quad \text{tensile failure} \\
\alpha \in [-73.38^\circ, 18.52^\circ) \quad \text{shear failure} \\
\alpha \in [-90^\circ, -73.38^\circ) \quad \text{compressive failure}
\end{array} \right.
\end{align*}
\]

According to the rupture types and occurrences of the MS events in Table 3, the R-values of events No. 1, No. 2, No. 3, No. 7, No. 8, No. 10, No. 11, No. 12, and No. 13 in event A are all located in [-30, 30], and all dislocation angles are less than 19.42°, which indicates that these events are dominated by shear ruptures or related to fault slips. Especially for events No. 2, No. 3 and No. 13, the dislocation angles are almost 0° and therefore are dominant in the focal mechanism. For event B, most of the R-values and the dislocation angles conform to the tensile failure mechanism of discrimination.

Most of the event G-values and dislocation angles in event B are consistent with the mechanism of tensile failure. Further analysis of the values in the table shows that most of the R-values corresponding to the mixed fracture are very close to the critical point of the judgement value (events 9, 10, 13, and 17), which are in or near the

### Table 2. Resolved fault plane solutions and the preliminarily inferred source types.

| No. | Strike | Dip | Strike | Dip | R   | α   | Tag               |
|-----|--------|-----|--------|-----|-----|-----|-------------------|
| 1   | 188.67 | 82.85 | 77.64 | 19.26 | 32.61 | 34.04 | Tensile failure |
| 2   | 201.61 | 77.41 | 101.89 | 52.91 | 32.17 | -23.16 | Tensile failure |
| 3   | 196.23 | 81.51 | 100.73 | 57.31 | 30.05 | 34.1  | Tensile failure |
| 4   | 197.78 | 81.58 | 102.23 | 56.8  | 29.8  | 34.05 | Tensile failure |
| 5   | 229.77 | 65.03 | 123.78 | 59.39 | 28.39 | 31.24 | Tensile failure |
| 6   | 240.85 | 53.49 | 111.67 | 49.52 | 36.51 | 30.34 | Tensile failure |
| 7   | 295.11 | 85.32 | 75.94  | 79.9  | 30.61 | -31.43 | Shear failure   |
| 8   | 198.62 | 79.24 | 100.99 | 55.04 | -31.19 | 28.34 | Unknown          |
| 9   | 200.31 | 78.04 | 100.7  | 51.75 | 31.4  | -25.43 | Shear/Tensile failure |
| 10  | 196.88 | 79.16 | 99.04  | 54.53 | 31.2  | -29.38 | Shear/Tensile failure |
| 11  | 199.91 | 77.84 | 100.64 | 53.23 | -31.94 | 24.68 | Unknown          |
| 12  | 198.12 | 77.33 | 98.1   | 52.28 | 32.31 | 24.72  | Tensile failure |
| 13  | 192.39 | 88.89 | 101.88 | 65.27 | 27.91 | -41.16 | Shear/Tensile failure |
| 14  | 197.31 | 78.29 | 98.42  | 53.28 | 31.59 | 27.97  | Tensile failure |
| 15  | 235.72 | 48.99 | 79.97  | 43.64 | 48.38 | 31.12  | Tensile failure |
| 16  | 100.5  | 73.04 | 8.53   | 83.58 | 26.38 | 44.36  | Tensile failure |
| 17  | 201.61 | 72.02 | 99.45  | 48.54 | 31.4  | -23.88 | Shear/Tensile failure |
| 18  | 194.01 | 85.1  | 101.25 | 60.69 | 28.65 | 39.18  | Tensile failure |
| 19  | 100.74 | 65.49 | 191.17 | 89.05 | 27.89 | 41.98  | Tensile failure |
| 20  | 85.38  | 85.03 | 353.44 | 68.75 | 21.11 | -40.53 | Shear failure   |

### Table 3. Spatial distribution of the stress principal axes.

| Zone | Number of MS events | σ₁ Azimuth | Dip | σ₃ Azimuth | Dip | R |
|------|---------------------|------------|-----|------------|-----|---|
| Event A | 116 | 276.67 | 68.31 | 56.79 | 16.97 | 0.25 |
| Event B | 121 | 37.60 | 57.18 | 147.12 | 12.16 | 0.72 |
mixed fracture. However, considering that the dislocation angles of each event are far greater than 18.52° and the R-values of the MS events are close to 30, based on the dislocation angle having a clear physical meaning, the rock damage type of the surrounding rock of the main transformer chamber vault presents a higher probability of tension failure.

Figure 13. Temporal evolutions of fracture mechanism in collapse process of rock masses. (a) Event A, (b) event B.

Figure 14. Spatial distribution of the stress principal axes. (a) Pole diagram of in-situ principal stress axes, (b) axial diagram of principal stress in event A, (c) axial diagram of principal stress in event B.
At the same time, the moment tensor inversion theory is used to calculate the time evolution of fracture mechanism in the damage area of events a and B, as shown in Figure 13(a) and 13(b). The dot in the figure represents the MS event, and its size represents the logarithm of the MS energy radiated by the MS event.

4.3. Analysis of stress field characteristics

Since the focal mechanism method can only solve the spatial occurrence of principal stress axis, only the occurrence data of principal stress axis of original rock are listed for comparative analysis. Figure 14(a) shows that the dominant orientation of the principal stress axis of the original rock stress field of the underground powerhouse is significant. The direction of the maximum principal stress axis is NWW-SEE, and the dip angle of the principal stress axis is close to horizontal; the medium principal stress axis is close to vertical. The occurrence of the principal stress axis of the original rock at 10 measuring points is very consistent. Based on the IJIM, 237 MS events collected in the MS event clusters were calculated via the principal stress axis, and the calculation results are shown in Figure 14.

There are 116 MS events in event A area. The direction of maximum principal stress changes gradually, and the dominant direction of maximum principal stress axis changes from NWW to NW; consistent with the fault strike, because event A area is located near fault f1-1-3; the dominant direction of minimum principal stress axis is NE-SW, which is consistent with the measured minimum principal stress, and the dip angle of middle principal stress axis changes from vertical to horizontal. The stress is controlled by the tectonic stress field, and the MS events are mainly the release of residual tectonic stress. There are 121 MS events in area B, the dominant orientation of the maximum principal stress axis is NE-SW; the dominant orientation of the medium stress axis is NWW-SEE; the principal pressure and medium stress axes are completely different from the original rock stress field; through coordinate transformation of the three stress axes of moment tensor rupture, the corresponding stress field distribution can be obtained in the geodetic coordinate system, and the tensile principal stress orientation is approximately perpendicular to the powerhouse Axis, pointing to the free surface. The MS event in this area is due to the excavation unloading caused by the construction of the bus tunnel, which leads to the deformation of the surrounding rock of the vault to the free face, resulting in the tensile failure to the tunnel.

Figure 14(b) and 14(c) shows the spatial distribution of the principal stress axis with 100 random noises and the corresponding shape ratio $G$ obtained using the IJIM, where the G-value can be expressed as:

$$G = \frac{\sigma_1 - \sigma_2}{\sigma_1 - \sigma_3}$$ (20)

According to Eq. (20), the larger the G-value is, the closer the eigenvalues of the intermediate principal stress and the minimum principal stress are. In the case of deviator stress only, the intermediate stress axis also shows the properties of tensile stress. In the extreme case of $G = 1$, the tensile stress state of the intermediate stress
axis and the minimum principal stress axis is consistent as the uniaxial compression state. In contrast, the smaller the \( G \)-value is, the more obvious the compressive stress of the intermediate stress axis is. We can perform a better analysis of the types of stress fields with the help of the \( G \)-values.

### 4.4. Discussion

According to the above analysis of the source mechanism and stress distribution of event A and event B in the MS event clusters, there are more events in Event A, and their focal mechanisms are more complicated. As can be seen from Figures 10 and 13(a), the damage area of event A is dominated by shear fracture mechanism, with relatively few tensile or mixed fracture mechanisms. The radiant energy values of partial shear rupture events and partial tension-shear events induced by faults are relatively large.

By the Hudson source-type diagram, the focal mechanism of Event A MS events is roughly divided into two types. There are two zones on the diagram. Part of the event is gathered at the center of the Hudson source type graph. Another event is clustered in the upper left quadrant of Hudson source type graph. It shows that these events clustered in the center may be related to shear fracture or fault slip while another part of the MS events is related to tensile damage or crack opening, according to the analysis of the focal mechanism at specific locations, Events No. 6 and No. 14 are primarily caused by extrusion and are related to rock collapse. Events 4, 5, and 9 are primarily tensile failures. Although they are located in fault zones, they are primarily caused by the interaction between fault and excavation and have no direct relationship with fault slip. The fracture mechanism of other MS events is related to shear fracture. Although these MS events are located in the fault zone downstream of the underground powerhouse and are dominated by shear failure, it is difficult to conclude that they are directly related to fault slip because of the different focal mechanisms of these events. By analyzing the evolution law of MS event fracture mechanism, we can conclude that the MS event Incubation Mechanism in event a damage area can be summarized as follows: excavation unloading induces the shallow surrounding rock to have a small energy tension fracture event; cracks propagate and propagate along the direction of the dislocation zone, and tension, shear and mixed events occur alternately, most of which are shear fracture and tension, shear fracture; the fracture extends to the fault structural plane The stress concentration results in shear fracture with high energy.

The fault plane solution of events No. 1, 2, 3, 7, 8, 10, and 12 suggests that the ‘fault’ is a right-lateral strike-slip thrust (sloping fault), while events No. 11 and 13 suggest that the ‘fault’ is a right-lateral strike-slip normal fault (sloping fault) (Table 1). The strike and dip angles identified are different and are not consistent with the direction obtained by exploration. We infer that these three events are not direct fault slip events. They are the result of the interaction between fault and excavation and experience the dual effects of shear failure and compression failure. However, from the moment tensor decomposition (Table 1) and their positions (Figure 11), events 7 and 10 are direct fault-slip events. These two events show a similar focus mechanism. The DC components of
the moment tensor of the two events indicate that fault F1-1-3 is a reverse fault. The inverse fault stratification is basically consistent with the direction and dip angle of the fault (obtained through exploration). However, the resolution dip angles of Events 1 and 12 are 20.67° and 30.68°, respectively. The angle is less than the value obtained by exploration. These events may have experienced shear fracture and crack opening, leading to slippage not along the actual fault plane. Figure 14(b) and 14(c) shows the spatial distribution of the principal stress axis with 100 random noises added to the focal mechanism solution. Combined with the data in Table 3, the maximum principal stress in area A is in the NW direction with a steep inclination angle, while the minimum principal stress is near the NEE direction with a horizontal inclination angle and the R-value is 0.25. In this region, the compressive stress of the intermediate stress axis is obvious, and the tectonic stress presents a state of near-biaxial compression and uniaxial tension. The stress tensor inversion results show the main stress state in strike-slip.

Event B has many events, but the focal mechanism is relatively clear. It can be seen from Figures 11 and 13(b) that the damage area of event B is dominated by tension fracture and tension shear fracture mechanisms, while shear and compression shear fracture mechanisms are relatively less; compared with the MS events in the damage area of event A, the radiation energy value of tension fracture and mixed events induced by excavation in event B is relatively low. According to the Hudson source-type diagram, MS events in Event B are associated with tensile failure or crack opening because most of these events are clustered in the upper left quadrant of the Hudson source-type diagram. At the same time, the source mechanism of the specific location is analysed through the table. Events No. 9, 10, 13 and 17 are primarily shear failures, while other events are tensile failures. The spatial distribution diagram of the stress axis is analysed. The direction of the tensile principal stress is approximately perpendicular to the axis of the powerhouse, and the R-value is 0.72. Within this area, the tensile stress of the intermediate stress axis is obvious, and the tectonic stress presents a state of near-uniaxial compression-biaxial tension. Combined with the site situation, because of the formation of a new facing surface during the excavation of an underground cavern, the rock mass around the cavern is unloaded horizontally, but it is essentially equivalent to the rock mass undergoing the loading process. Therefore, under the action of horizontal or vertical principal stress, the surrounding rock mass in the disturbed area around the cavern is prone to produce unloaded tensioned cracks.

5. Conclusions

Based on the rock mass rupture signals obtained from MS monitoring, moment tensor solution analysis and inversion of MS events are conducted. The fracture mechanism and regional stress field distribution of these precursor sources are deeply analysed, and the geometric characteristics of the fracture surface are studied. The following main conclusions are obtained.

(1) Based on the characteristics of dense underground caverns and sophisticated geological structures, noise reduction of MS signals can effectively improve the waveform quality. Some modifications were made to the calculation and decomposition of
the moment tensor considering the viscous attenuation of waveforms and the unavoidable conditions of single component signals. A complete and accurate process of mass spectrum data processing in an underground powerhouse was established.

(2) The MS accumulation of underground caverns was affected by many factors. Through quantitative analysis of the MS event cluster characteristics and stress field distribution of the underground powerhouse at the Houziyan hydropower station, the rupture mode of event A was characterized by shear failure and extension-shear failure. The rupture mode of the dome roof of the main transformer room was dominated by a tensile fracture. The results obtained from moment tensor inversion can well reflect and explain the failure mechanism of the surrounding rock, which is consistent with the actual situation, and the method of using the moment tensor to analyse the failure mechanism of the surrounding rock of the underground powerhouse is feasible.

(3) Through the combination of MS technology and moment tensors, not only can the space-time evolution mechanism of rock fractures be obtained but the fracture type and direction of the seismic source can also be described in detail, and the interaction between rock microfractures and their extension and penetration mechanism can be understood at a deeper level.

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Data availability statement

The data used to support the findings of this study are available from the corresponding author upon request.

Disclosure statement

No potential conflict of interest was reported by the authors.

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