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Developments and prospects of microseismic monitoring technology in underground metal mines in China

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Abstract: Microseismic monitoring technology has become an important technique to assess stability of rock mass in metal mines. Due to the special characteristics of underground metal mines in China, including the high tectonic stress, irregular shape and existence of ore body, and complex mining methods, the application of microseismic technology is more diverse in China compared to other countries, and is more challenging than in other underground structures such as tunnels, hydropower stations and coal mines. Apart from assessing rock mass stability and ground pressure hazards induced by mining process, blasting, water inrush and large scale goaf, microseismic technology is also used to monitor illegal mining, and track personnel location during rescue work. Moreover, microseismic data have been used to optimize mining parameters in some metal mines. The technology is increasingly used to investigate cracking mechanism in the design of rock mass supports. In this paper, the application, research development and related achievements of microseismic technology in underground metal mines in China are summarized. By considering underground mines from the perspective of informatization, automation and intelligentization, future studies should focus on intelligent microseismic data processing method, e.g., signal identification of microseismic and precise location algorithm, and on the research and development of microseismic equipment. In addition, integrated monitoring and collaborative analysis for rock mass response caused by mining disturbance will have good prospects for future development.

Key words: underground metal mine; microseismic; safety management; rock mass stability; disaster warning; integrated monitoring

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1 Introduction

Microseismic monitoring technology, which detects elastic waves generated by rock mass fracturing, has been shown as a valuable tool to monitor rock mass stability. Since microseismic signals are generated by the propagation and expansion of cracks, each microseismic signal contains plentiful information about the structural changes inside the rock mass. Thus, it can provide support for risk assessment and warning of ground pressure hazards, such as collapse, caving, spalling, landslide, and rockburst. The traditional test

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methods for stress and deformation can only obtain point, line or surface information. Compared to that, the temporal-spatial evolution laws of microseismic parameters, e. g., event cluster, energy release and magnitude, calculated by statistical geophysics theory can provide three-dimensional of changes in stress and deformation inside rock mass. This three-dimensional information is useful in engineering design and in the research of rock mass mechanics.

As natural resources at shallow depths are gradually exploited, deep mineral resource exploitation is becoming increasing common in the mining industry. In Australia, the deepest mines are currently between 1000 and 1900 m below ground level; in Canada, they vary from 1500 to 3000 m; and in South Africa, where most of the deepest mines in the world are located, mining depths can reach 3000 to 4000 m. Since 1970s, microseismic technology began to be used to monitor the deep mining process, and then it gradually became an important tool in the safety management of mines [1−6]. With the advances in computer technology in recent decades, the capability of rapidly processing seismic waves has made microseismic technology more broadly applicable. The microseismic systems produced by companies of the Engineering Seismology Group (ESG) in Canada and the Institute of Mine Seismology (IMS) in South Africa are widely adopted in the world for their advantages of high reliability and sampling precision, powerful data processing functions and long time stability.

The metal mines in China entered into the deep mining much later than in Australia, Canada and South Africa. Microseismic technology was introduced to China in 21st century. LI et al [7, 8] introduced a 16-channel microseismic system produced by ESG to Fankou lead-zinc mine to continuously monitor the crack generation and propagation in rock mass in real-time. Through cooperation with the Commonwealth Scientific and Industrial Research Organization (CSIRO) in Australia, JIANG et al [9, 10] developed a microseismic system for coal mines. After that, microseismic technology has been gradually adopted in deep metal mines in China, which was mainly promoted by the university-enterprise cooperation, for example, Central South University and Dongguashan copper mine [11, 12], and Northeastern University and Hongtoushan copper mine [13 − 15] cooperation. Besides metal mines, microseismic technology was also applied in many other rock excavation projects for the evaluation of rock mass stability and dynamic warning of disasters, such as coal mines [16 − 18], deep buried tunnels [19−21], hydropower stations [22−24], slope engineering [25−27] and Sichuan-Tibet railway [28]. To reduce the occurrence of accidents, the safety monitoring system was implemented by the Government of China in all underground mines since 2010. Microseismic monitoring system has been employed by more than 40 underground metal mines in China by the end of 2019.

Before 2000, there were only two underground metal mines in China with the mining depth of approximately 1000 m, namely, Dongguashan copper mine and Hongtoushan copper mine. At present, there are 16 metal mines with the mining depth greater than 1000 m [29]. Consequently, China ranks the third in the list of countries having deep underground metal mines (the number of metal mines with mining depth of more than 1000 m in Canada and South Africa are 28 and 27, respectively). At the current rate of mining depth extension, there will be more than 30 metal mines in China entering into the deep mining category, i. e. the mining depth beyond 1000 m, and China will rank the first in the number of deep mines by the end of 2025. It indicates that deep mineral resources exploitation in China will become commonplace [30 − 32]. On the other hand, the costs of ore transportation, mining and filling process during deep mining are much higher compared to shallow mining. To ensure economic efficiency, the mining scale has to be markedly increased. For example, the designed annual production in Sishanling iron mine and Macheng iron mine in China has reached up to 15 million tons, which is almost twice compared to the previous annual production in the shallow mines. Under high ground stress conditions in deep metal mines, frequent and strong mining disturbances can easily lead to spalling and collapse of the surrounding rock mass, even generating dynamic hazards such as rockburst. These ground pressure hazards can easily result in casualties, equipment damage and interruption of production. For instance, rockburst killed four workers in Falconbridge mine [33], and seriously damaged four mining sublevels in Kidd mine in Canada.

Therefore, the management for ground pressure hazards has become a challenge in deep mining. As an effective tool for the evaluation of rock mass stability and warning of dynamic disasters, microseismic monitoring technology will play an important role in deep metal mines in China.

2 Principle of microseismic monitoring technology

2.1 Monitoring principle

When the stress is redistributed in the rock mass due to human activities such as mining, sudden slip or shear may occur along pre-existing joints, and new cracks may generate in region with high stress. These movements or failures result in the release of energy in the form of seismic waves and are known as microseismic events. During such events, P- and S-waves (compressional and shear stress waves), radiate away from the fracturing source in rock mass and, as these waves pass a sensor, a seismogram is recorded, as shown in Figure 1. These analog signals recorded by sensors are sent to a data acquisition instrument for amplification and digitization. Then, the digitized data are transmitted to the central server through the data transfer unit. The recorded seismograms thus can be shown through display software. Also, the source parameters of the microseismic event, such as origin time, three-dimensional location, radiated energy, and seismic moment, can be calculated based on the recorded data. Finally, the space-time microseismicity during the rock mass fracturing process can be established and analyzed. Because an elastic wave can travel a relatively long distance of hundreds of meters, microseismic technology can be used for wide-range monitoring. By deploying many microseismic sensors, the whole mine can be effectively monitored.

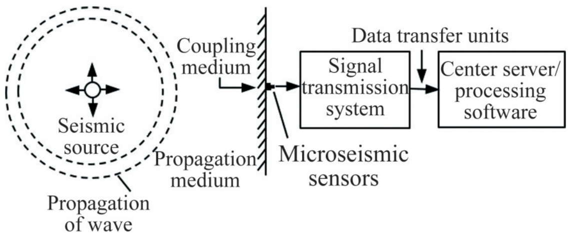


Figure 1 Schematic diagram of principle of microseismic monitoring

2.2 Sensor layout

Monitoring of a mine can deploy a combination of sensor network for large scale mining areas monitoring and local region monitoring. For large scale area monitoring, sensors are arranged in pre-existing tunnels at each sublevel as shown in Figure 2(a). As the mining areas are usually thousands of meters long, sensor layouts should cover the whole mining areas as much as possible. Each area should be covered by a minimum number of sensors to satisfy the microseismic location calculation requirement. It is better to arrange some triaxial sensors to improve the calculation accuracy of microseismic position and source parameters. In addition, it should be noted that mining process will form many goafs, and the location accuracy of microseismic events would be influenced when signals pass through these goafs. Therefore, enough sensors need to be arranged at each side of the goaf to meet the requirement of location calculation. Many mining methods are used according to the orebody condition. For one stope, it may be mined from top to bottom, from bottom to top or from middle to two sides. An example of sensor layouts for a stope mined from middle to two sides is shown in Figures 2(b) and (c). The majority of sensors are arranged prior to mining by using pre-existing tunnels, and some sensors are added during the mining process.

2.3 Microseismic parameters

Due to the complexity of underground mining environment, rock mass damage cannot be completely estimated from single microseismic event. According to the view of seismology, statistical analysis on temporal and spatial evolution laws of microseismic events is widely used to judge rock mass stability by studying microseismic events within a certain time and region. There are many methods used for microseismic data analysis, which mainly divided into two categories as the machine learning methods and the statistical methods. The machine learning methods include neural network [35−37], clustering analysis [38], non-linear fuzzy comprehensive evaluation [39], ensemble learning [40], random forest [41], fuzzy logic [42], support vector machines [43, 44] and expert system [45].

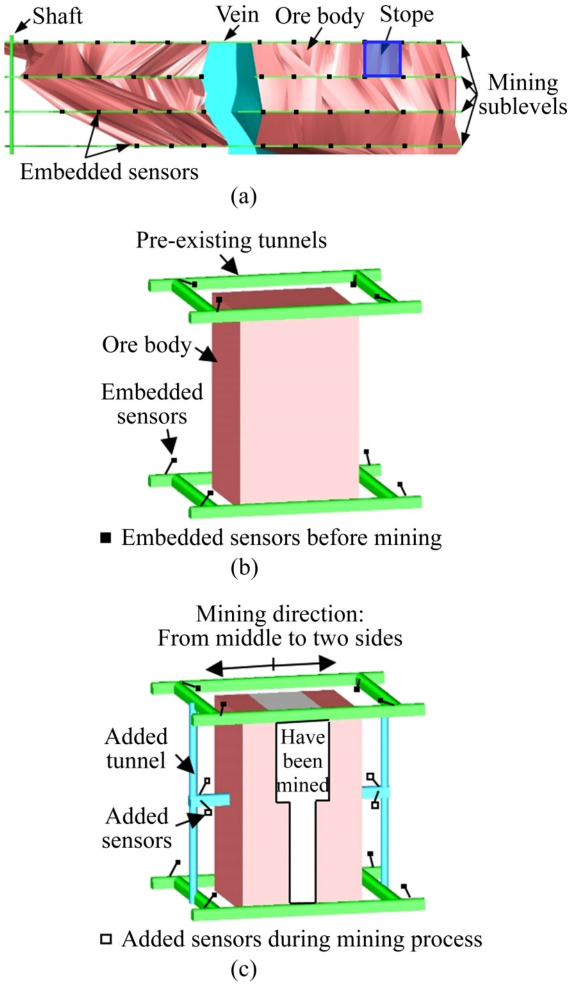


Figure 2 An example of sensor network for microseismic monitoring in mine: (a) Located using pre-existing tunnels at each sublevel for large scale monitoring; (b) Located for typical stope before mining; (c) Added in new tunnels during mining process (modified from Ref. [34])

The statistical methods mainly focus on the evolution laws of microseism source parameters [46−48]. General statistical parameters of microseismic activities for studying the temporal and spatial evolution of cracks inside rock mass are shown in Table 1.

3 Safety monitoring for mining process in underground metal mines

Under high stress condition, the deep mining process will inevitably result in stress redistribution and crack generation in rock mass. By the use of microseismic monitoring technology, the information of crack generation and propagation can be detected in real-time. Then, these microseismic data and the changes in microseismic parameters are applied to evaluate the rock mass stability, identify the potential region of hazards, and make qualitative or quantitative warning for the dynamic disaster. Moreover, the stress and deformation obtained from microseismic data can be used to evaluate the accuracy of mining process and to optimize mining parameters, and then to dynamically control the mining process.

3.1 Microseismic activities induced by mining disturbance

During deep mining process, rock masses are inevitably subjected to frequent disturbances. The disturbances can be classified into two types: 1) unloading effects caused by the stress changes in the surrounding rock mass after ore is mined; and 2) dynamic disturbances, such as blasting. Therefore, rock mass in deep mines is under the stress state of “high stress+dynamic disturbance” [56]. When the elastic strain energy stored in rock mass is released sharply by stoping, the surrounding rock mass is prone to loosening and failure near the stope by the unloading effect [57, 58]. By analyzing the relationship between the mining process and microseismic parameters in Dongguashan copper mine, YANG et al [59] found that the microseismic parameters, including activities, stress and deformation near the stope, remarkably increased with an increase in ore production. For the same mine, TANG et al [60] studied the changes in cumulative apparent volume (ΣV_A), and cumulative excavation volume (ΣV_m). Based on the quantitative seismology, a linear relationship was found between mining rate reflected by cumulative excavation volume and rock mass deformation inferred by apparent volume, as shown in Figure 3.

After stoping, surrounding rock mass near the stope needs a certain time for returning to a stable state. Within this period, hazards due to ground pressure are prone to occur and pose a threat to the workers. The modified Omori Law (MOL), which represents the number of aftershocks $N(t)$ measured at time t after the time of the main earthquake and is written as $N(t)=A\cdot t^{-p}$, has been used by LIU et al [54] to analyze the power law decay characteristics of microseismic activities after stoping in

Table 1 Statistical parameters of microseismic activity for rock mass risk assessment [49−55]

Parameter	Explanation
Event rate	Number of microseismic events generated per unit time, which is used to describe the frequency of microseismic events inside rock mass.
Energy release rate, E	Radiated energy of one event or in per unit time. It is an important index of rock failure intensity evolution.
Accumulative events	Total number of microseismic events generated in a certain time and region, which is used to evaluate the change in regional fracture activities.
Accumulative energy release	Total energy released by microseismic events in a certain time and region, which is used to reflect the degree of energy released by cracks generated inside rock mass.
Seismic moment, M_0	A powerful parameter for measuring the strength of a seismic source. $M_0 = \mu\bar{u}A$, where μ is the modulus of rigidity of the source, $\bar{u}$ is the average displacement, A is the area of the fault, and $A = \pi r_0^2$ (r_0 is the source radius).
Magnitude, M	The magnitude of an earthquake, which is used to describe the scale of the earthquake, whose types include local magnitude, moment magnitude, etc.
Seismic potency, P	It represents the volume of rock, of whatever shape, associated with co-seismic inelastic deformation at the source. For a planar shear source, the potency is defined as $P = \bar{u}A$.
Apparent stress, σ_a	The apparent stress is the ratio of the total radiated seismic energy to the seismic moment. It assesses the amount of energy released per unit of deformation, defined as: $\sigma_a=\mu/M_0$.
Apparent volume, V_A	It measures the volume of rock with the change in inelastic shear strain and is written as $V_A=M_0^2/2\mu E$. Apparent volume, like apparent stress, depends on seismic potency and radiated energy, and because of its scalar nature, it can easily be manipulated in the form of cumulative or contour plots.
Stress drop, $\Delta\sigma$	Stress drop is used to describe stress adjustment and release of the source, which is related to the source radius.
Energy index (EI), I_E	The energy index, I_E, of a microseismic event is the ratio of the observed radiated seismic energy E of that event to the average energy $\bar{E}\left(M_0\right)$ radiated by events of the same seismic moment. Because lg$E$ versus lg$M$ usually produces a linear relationship (where $\lg E=c_1\lg M+c_2$), EI can be written as: $I_E = \dfrac{E}{\bar{E}\,(M_0)} = \dfrac{E}{10^{c_1 \lg M_0 + c_2}} = 10^{-c_2}\dfrac{E}{{M_0}^{c_1}}$
Event density	Number of microseismic events per unit volume, which is used to describe the cluster extent of microseismic events.
Energy density	Amount of radiated energy per unit volume, which is used to describe the release degree of microseismic events.
Fractal dimension	It is an index to describe the irregularity of microseismic activities. For example, before rock failure, the spatial distribution of microseismic events changes from random to ordered, which is accompanied by a decrease in value of spatial fractal dimension.
b value	In the relationship between earthquake magnitude and frequency (G-R relationship): $\lg N=a-bM$. The *b* value is a useful parameter to analyze the seismic magnitude and frequency. It is of great significance to study the proportion of cracks at different scale and the process of small- to large-scale crack growth.
High-energy event	The microseismic event with energy exceeding a certain value per unit time, which is used to evaluate the risk of hazards.
Schmidt number	Seismic Schmidt number is the ratio of kinematic viscosity to diffusion. It measures the spatio-temporal complexity of the seismic flow of rock. The lower the seismic Schmidt number, the less stable the flow.
Z value	Difference between the mean values of sample seismic moment and long-term seismic moment. *Z* value will reduce to its minimum value when rockburst is occurred.
η value	It is the correction coefficient of the relationship between earthquake magnitude and frequency, describing the degree of linear deviation of the fitting curve. $\eta = \dfrac{<X^2>}{<X>^2}$, where $X=M-M_0$; "< >" expresses the mean value.

Hongtoushan copper mine. Figure 4 shows that the microseismic activities were closely related to the interval between blasts, e.g., the shorter the interval between blasts, the higher the number of microseismic events that were recorded. After each stoping, the surrounding rock required a certain time to recover to a relatively stable state, accompanied by stress adjustment and redistribution. As shown in Figure 4, the fitting results by MOL indicated that the microseismic sequences corresponded to the

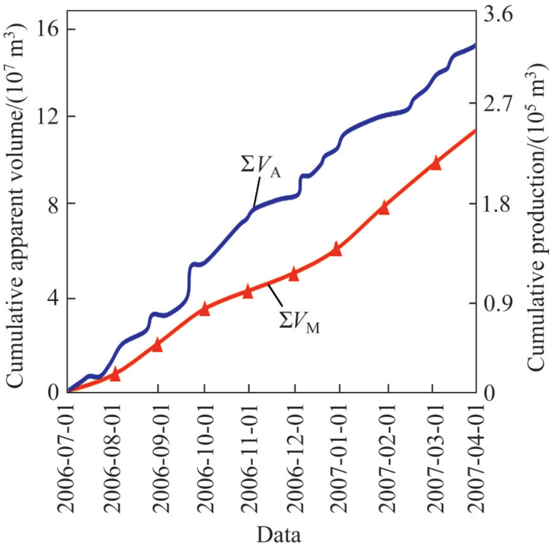


Figure 3 Time-history curve of cumulative production and cumulative apparent volume (modified from Ref. [60])

power law decay characteristics. The time to return to stable state of rock mass after stoping can be obtained by analyzing the background microseismic activities from no mining stope.

For high-production mines, especially those that use medium-length hole blasting or long-hole blasting, the explosives used can be more than hundreds of kilograms or even several tons for one blasting. Strong blast disturbances can easily lead to spalling and collapse of the surrounding rock of tunnels, even generating dynamic hazards, such as rockbursts [54, 61 − 63]. Statistical data show that two-thirds of mine rockbursts occur within a short time after blasts [64]. For example, more than 20 m of the roadway in the Hongtoushan Copper Mine, one of the deepest nonferrous metal mines in China, was damaged by blasting vibrations at a mining depth of 1000 m [14]. In the Gujiatai Iron Mine, a blasting disturbance caused the collapse of a large rock mass in a stope, and production was subsequently suspended for several years, resulting in a serious economic loss. Thus, the relationship between microseismic activities and blasting has attracted the attention of researchers. A good consistency of the occurrence time between blasting process and microseismic events, shown in Figure 5, was introduced by TIAN et al [65] by analyzing the relationship between them. By conducting continuous real-time monitoring of microseismic events for the medium-length hole with extra-large blasting process in Shizhuyuan mine, the explosive comsumption was approximately 437 tons. HU et al [66] studied the spatial and temporal distribution of aftershocks, and obtained the most intense period and region prone to failure after blasting.

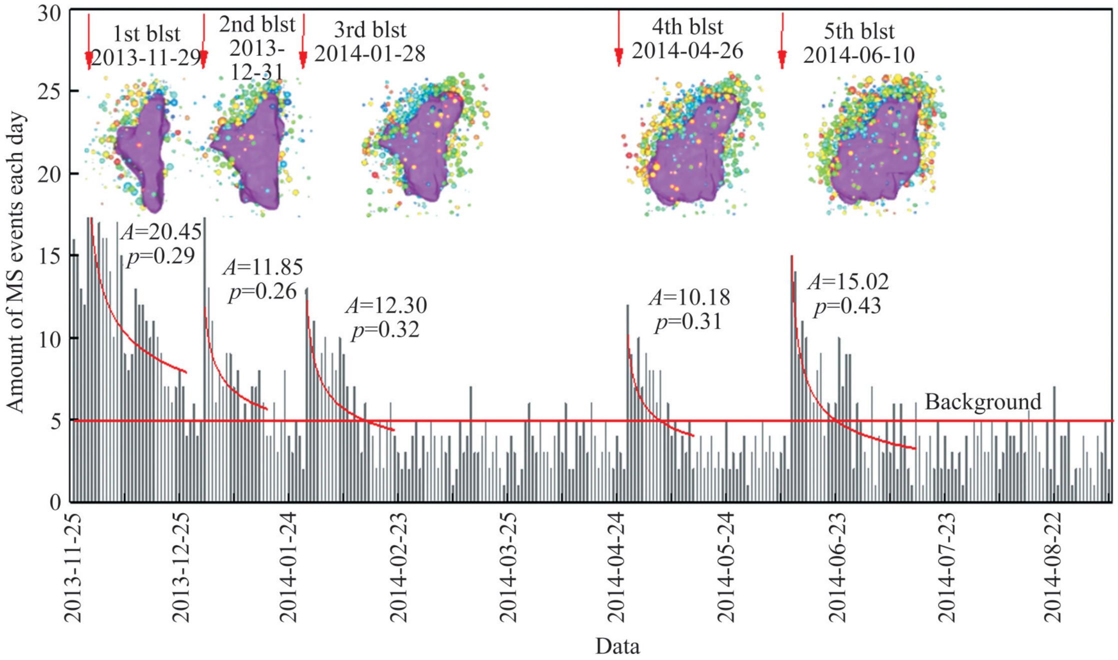


Figure 4 Temporal-spatial evolution laws of microseismic events and its power-law decay characteristics in Hongtoushan copper mine (modified from Ref. [54])

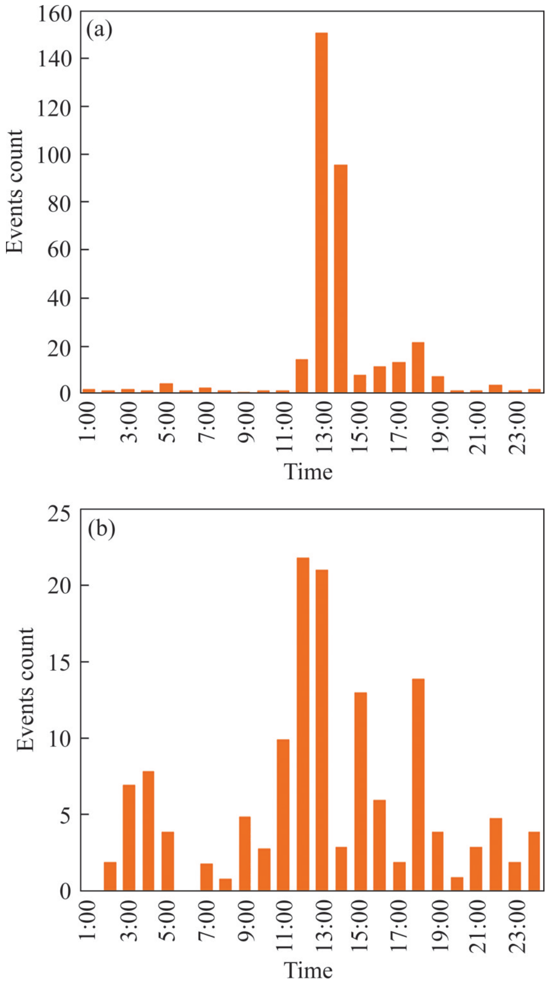


Figure 5 Comparison of occurrence time of blasting process (a) and microseismic event (b) (modified from Ref. [65])

In a deep metal mine, underground constructions, such as tunnel, ramp and shaft, are the main workplace for workers. In general, the time for workers to re-enter the workplace is mainly decided by the time of smoke dissipation after blasting, and rarely by considering the stability of surrounding rock mass. From the analysis of the distance between the blasting area and the monitoring area, as well as the time required for the rock mass in ramp to return to the stable state, a linear relationship was found by LIU et al [67] as shown in Figure 6. The result provides useful information to evaluate the time at which workers can re-enter the ramp. For example, workers should delay to re-enter the workplace that is close to the blasting center.

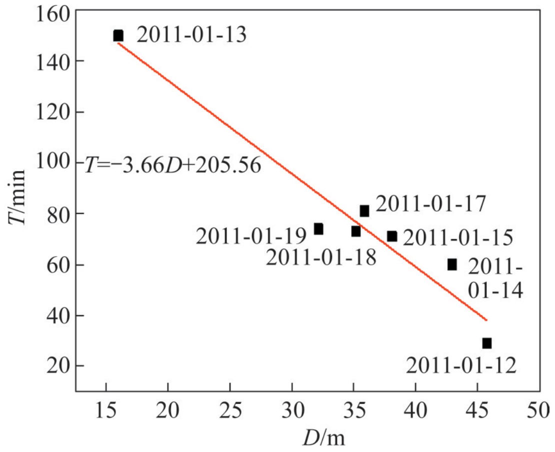
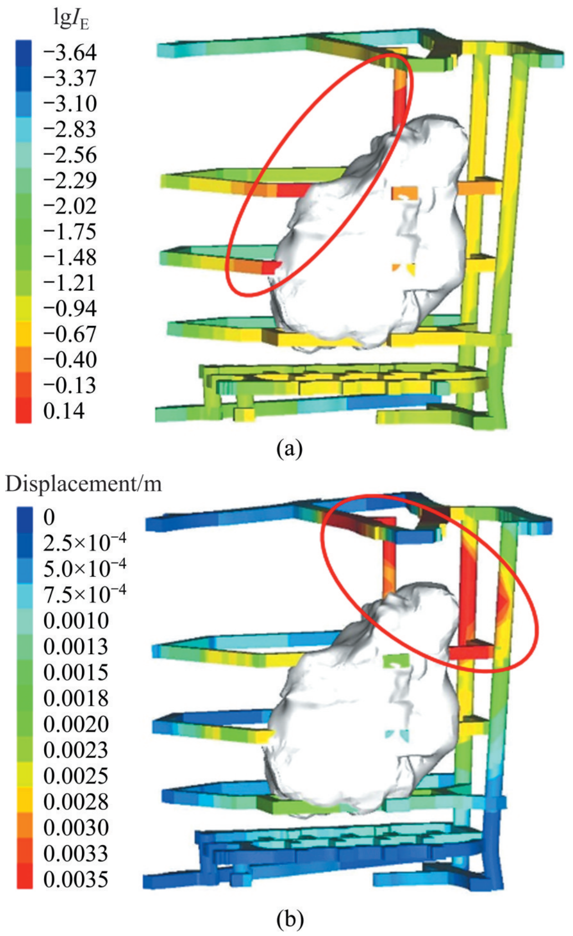


Figure 6 Relationship between blasting distance and time for rock mass in ramp to return to the stable state (modified from Ref. [67])

3.2 Risk assessment and warning of rock mass hazards

The distribution and evolution laws of stress and deformation are important in the research of rock mass mechanics. Compared to traditional testing techniques, microseismic data can provide 3-D information of changes in stress and deformation inside rock mass. For instance, as explained in Table 1, apparent stress is a ratio of the total radiated seismic energy to seismic moment, assessing the amount of energy released per unit of deformation. Large apparent stress values are indicative of increasing stress conditions within the rock mass, and vice versa. Similar to apparent stress, apparent volume depends on seismic potency and radiated energy, and because of its scalar nature, it can easily be manipulated in the form of cumulative or contour plots. Based on the analysis of microseismic data, the stress and displacement distributions and evolutions have been widely used to assess the rock mass stability and forecast dynamic hazards to better manage disastrous rock failures [15, 52, 54, 67].

Since the changes in stress and deformation are independently obtained from microseismic events, these changes can reflect the differences in the physical mechanics throughout the rock mass. The source of a microseismic event associated with a weaker geological feature or with a softer area of the rock mass under lower differential stress radiates less seismic energy per unit of inelastic co-seismic deformation is compared to an equivalent source associated with a strong and highly stressed rock mass. The phenomenon of an increase in deformation and decrease in stress indicates that the rock mass is degrading. In contrast, the integrity of the rock mass is better. This is important to the support parameter optimization. Figure 7 shows an example in which the dynamic disasters such as rockburst and ejection were more prone to occur in rock mass with better integrity and higher stress in the left hand side tunnels (circled in Figure 7(a)). Supporting measures such as installation of anchor bolts with high shock resistance, anchor bolts with high energy absorption properties and D-bolt anchors should be used to prevent and control dynamic disasters. On the other hand, the rock mass underwent large deformation in the right hand side tunnels and shafts (circled in Figure 7(b)), easily forming caving and stripping hazards. For this condition, measures such as application of shotcrete support and bolt-mesh support are very effective.



(a)

(b)

Figure 7 Contour map of apparent stress and displacement obtained from microseismic data: (a) Apparent stress; (b) Displacement (modified from Ref. [54])

It is well known that the fracture process of brittle rock mass is divided into three stages, including elastic deformation stage, strain hardening stage, and strain softening stage. By analyzing the changes in microseismic parameters, LIU et al [68] identified the tendencies of increased cumulative apparent volume and microseismic activities accompanied by decreased energy index as the precursors of rockburst, as shown in Figure 8. Based on the study, the warning point, i. e., the point between the strain hardening stage to the strain softening stage (Figure 9), was proved effective to predict rockburst in Huize lead-zinc mine.

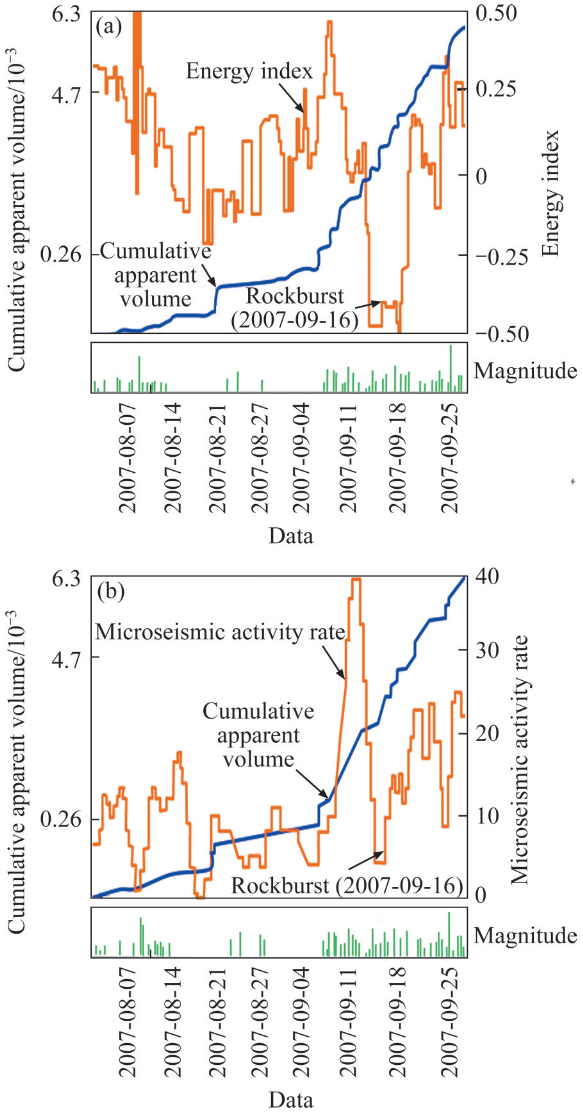


Figure 8 Time-history curve of microseismic parameters: (a) Energy index and cumulative apparent volume; (b) Microseismic acticvities and cumulative apparent volume (modified from Ref. [68])

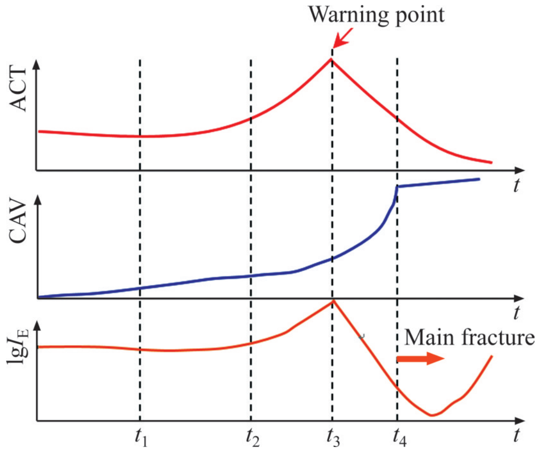


Figure 9 Variations of source parameters in process of rockburst (modified from Ref. [68]). (Note: ACT is the microseismic activities ratio, CAV is the cumulative apparent volume, $\lg I_E$ is the logarithm of energy index)

When conducting risk assessment of ground pressure hazards by using microseismic technology, some microseismic parameters may be influenced by the uncertainties in monitoring data, such as precision of locating microseismic events, sensitivity of monitoring system and artificial processing error. Therefore, comprehensive analysis of changes in multi-microseismic parameters can improve forecasting accuracy, which is meaningful to the application of microseismic monitoring technology in deep metal mines. Moreover, comprehensive analysis by numerical simulation and in-situ monitoring can provide valuable information to researchers and managers. YANG et al [69] presented a set of effective analysis procedure to evaluate the risk assessment of hazards induced by mining process as shown in Figure 10. The procedure was developed by considering the achievements of rock burst prevention and control in typical deep metal mines abroad and the microseismic monitoring in Dongguashan copper mine. There are four steps in this procedure. First, establish the hazards control strategy and the database of seismic events by analyzing the causes of seismic events occurred, rock mass failure type, and changes in microseismic parameters and waveforms. Second, perform back analysis for historical seismic events, particularly the changes in seismic parameters before and after the occurrence of rockburst, to obtain the prediction criteria of ground pressure hazards. Third, identify the area of high hazards by analyzing the spatio-temporal distribution and evolution of seismic events and the changes in seismic parameters. The mining process should be adjusted to reduce the risk of hazards. At last, calculate warning for dynamic disasters such as rock burst by establishing a prediction model, calculate the probability and grade of disaster occurrence, and formulate emergency management measures.

3.3 Mining parameters optimization

Under the high in-situ stress environment in deep mines, stress re-distribution after blasting would release the stored strain energy within the rock mass, and this would be accompanied by rock mass deformation and fracture. The range of rock mass deformation and fracture is closely related with the mining method, mining speed, structure parameters of the stope, and especially the mining sequence. There are many methods for mining sequence optimization such as engineering analogy method, similar material simulation experiment, and numerical simulation. The objective of mining sequence optimization is mainly for rock mass stability evaluation and risk management. Microseismic activity is an objective reflection of the rock mass response to a mining disturbance. Therefore, its behavior can be employed to evaluate the accuracy of mining process, and then to optimize mining parameters, so as to reduce the risk of rock mass failure and improve the production efficiency.

In deep mining practice, a tunnel is excavated much faster and more rock mass is broken after blasting than in a shallow project under the same excavation parameters, including cross-section size, blasting hole arrangement, and blasting parameters [56]. Therefore, large in-situ stress is conducive to rock breaking in a hard rock mass in deep mining. If methods can be devised such that this stored strain energy is used to break the rock mass during blast, less explosive can be used to reach the goal of efficient and safe mining. Based on this principle, FENG et al [70] and LIU et al [71] performed qualitative optimization for mining sequences and

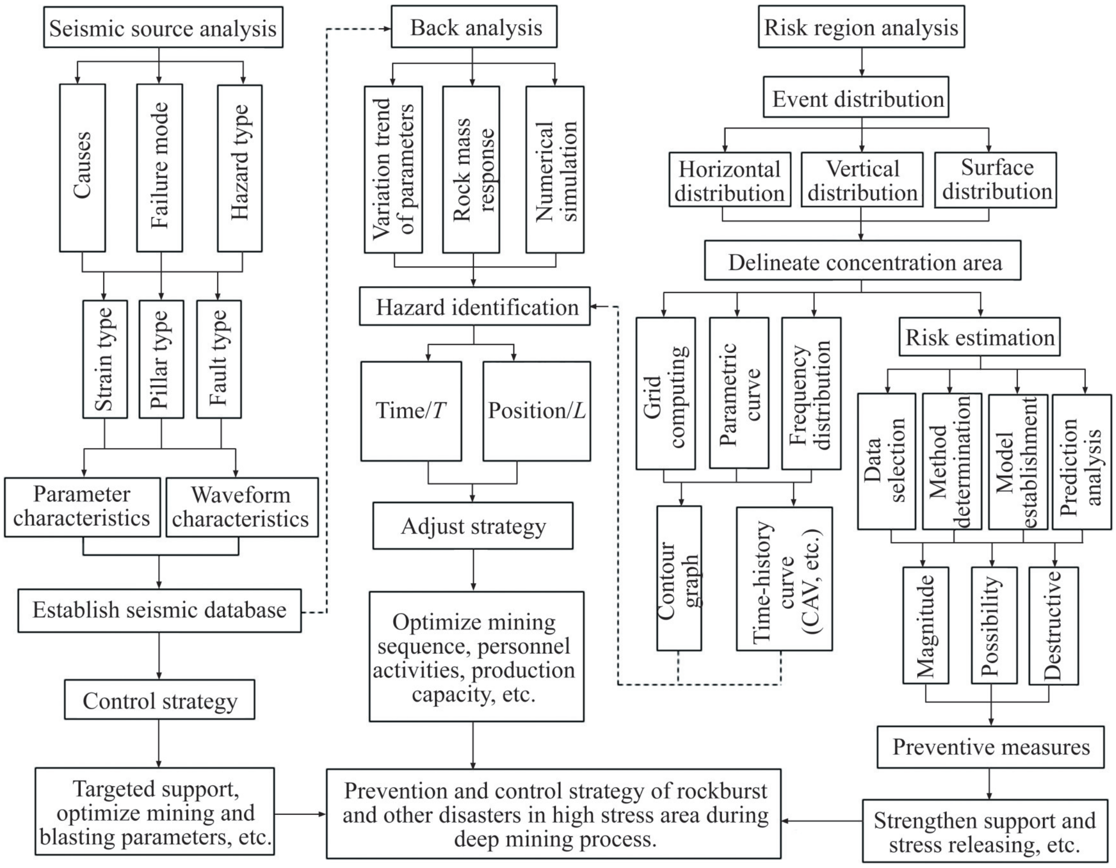


Figure 10 Working procedures for prevention and control of ground pressure hazards (modified from Ref. [69])

blasting parameters via the equivalent stress calculated from microseismic data. When at least two regions were prepared for stoping, the equivalent stresses of them were compared and the region with a higher equivalent stress was selected for mining, as shown in Figure 11. In addition, blasting parameters were changed to reduce the usage of explosive by utilizing the stored strain energy to break rock mass. The changes included reduced row spacing and increased hole-bottom spacing of the blasting holes. The results indicated that these measures effectively reduced the rock mass over breakage and under breakage, i. e., ore dilution and loss (shown in Figure 12). Moreover, these measures helped to reduce the explosive quantity and the blast vibration thereby contributing to maintain rock mass stability.

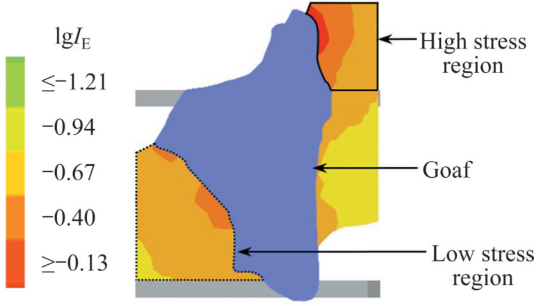


Figure 11 Mining sequence optimization according to $\lg I_E$ distribution (modified from Refs. [70, 71]).

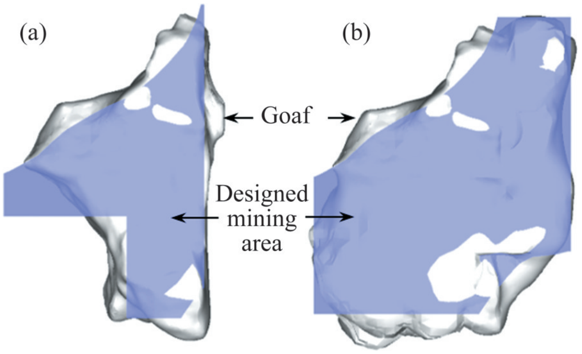


Figure 12 Morphology comparison of goaf and designed mining area before (a) and after (b) blasting parameters optimization (modified from Refs. [70, 71])

3.4 Seismic source mechanism

There are various types of rock mass instability failures in deep mining and the control measures should consider the failure mechanisms of different types of hazards. The seismic source mechanism, i. e., tensile, shear or mixed type of cracks, can provide a deeper understanding for rock mass failure process as well as guide the designs of the support measures and ground pressure hazards control. Three methods are commonly used to calculate the seismic source mechanism, namely, the polarity classification method, the ratio of E_s/E_p, and the moment tensor inversion. The latter two methods are more widely used in microseismic monitoring in metal mines.

E_s/E_p is a relatively common seismic source mechanism analysis method to examine the ratio of energy from the shear wave (S-wave) to the energy from the compression wave (P-wave). Researchers [6, 72−76] have suggested that the energy ratio is a strong indicator of the fracture mechanism. Figure 13 shows an example study of two typical rock mass damage and fracture processes in Hongtoushan copper mine and Ashele copper mine by using E_s/E_p. It shows that the E_s/E_p ratio distributions of microseismic events in the two cases are markedly different. For the non-shear fracturing mechanism, i.e., volumetric strain change due to the unloading effect in Hongtoushan copper mine, the E_s/E_p ratios of more than 62% of the microseismic events were under 3, and those of more than 70% were under 10. In contrary, almost 68% of microseismic events had an E_s/E_p ratio above 10 during the orebody slip failure in the Ashele copper mine. The results indicate that the method of utilizing the E_s/E_p ratio can be applied for evaluating the failure mechanism of rock mass.

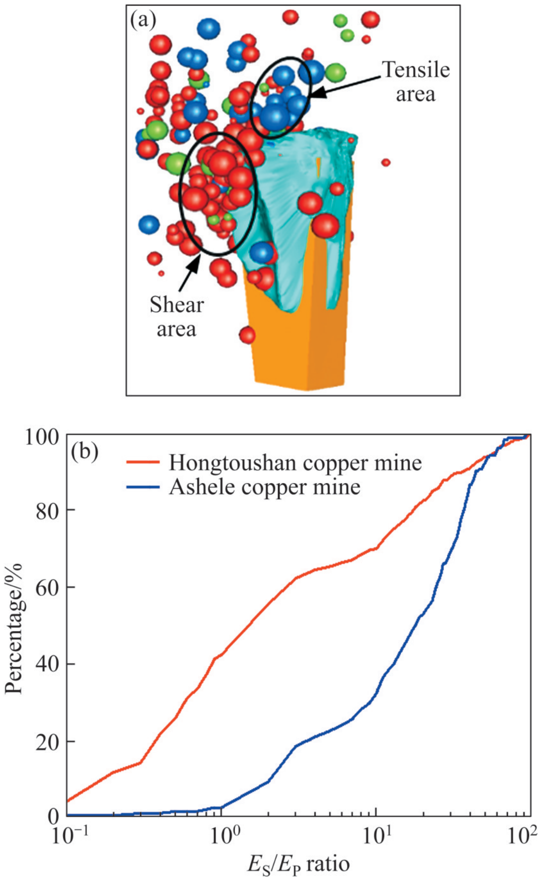


Figure 13 Rock mass fracture mechanism by mining disturbance in Hongtoushan copper mine and Asher copper mine based on E_s/E_p: (a) Microseismic events distribution during roof caving in Ashele copper mine; (b) Percentage of microseismic events to total events with different E_s/E_p ratios in two mines

The moment tensor inversion method was proposed by GILLBERT [77]. After that, many studies have been conducted on acoustic emission tests and in-situ microseismic monitoring, and the method has significantly contributed to the classification of fracture types and the relationship between fracture surfaces and principal stresses [78−83]. WU et al [84] indicated that the method of moment tensor inversion plays a vital role in the fields of disaster warning and prevention in rock mass engineering, and monitoring and control of hydraulic fracturing. LI et al [85] performed a back analysis of seismic source mechanisms of the overlying rock mass over the mining goaf induced by a large blast. The study showed that the precursory focal mechanism solution based on microseismic moment tensor theory can accurately determine the failure type of meso-scale engineering rock mass. MA et al [86] employed an optimized moment tensor inversion method using full waveforms to quantitatively determine the rock mass fracturing orientation and the type of rupture process, and proved that this method can quantitatively analyze the focal mechanism of mining-induced seismicity in fault zones and it provides beneficial understanding of mining-induced fault slips (Figure 14). TANG et al [87] applied moment tensor inversion method to analyze the failure mechanism of surrounding rocks in Dongguashan copper mine, as shown in Figure 15. The results showed that the major rock failure of roadway was shear failure, in combination with the action of multiple factors. When tunnels were located in different rock contact zones,

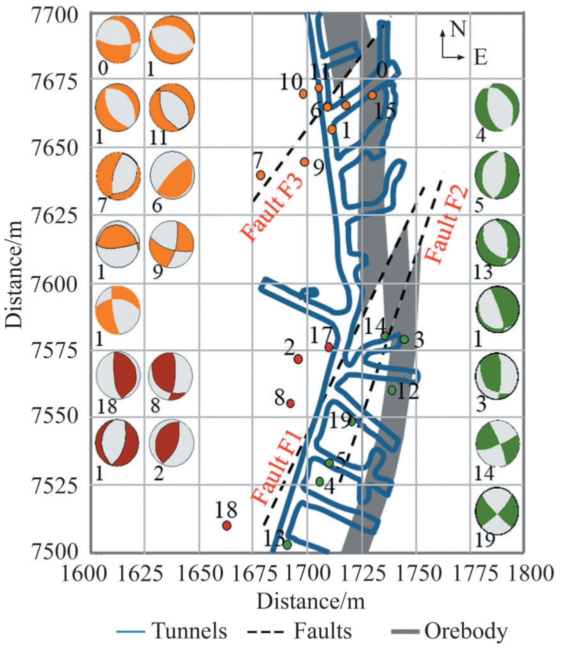


Figure 14 Plan of tunnels, orebody, faults, microseismic event locations and their focal mechanism (red color for events in fault F1 vicinities, green color for events in fault F2 vicinities, and orange color for events in fault F3 vicinities. Modified from Ref. [86])

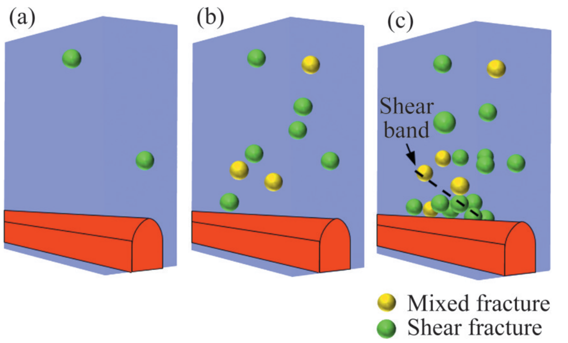


Figure 15 Focal mechanism of microseismic events: (a) Calm period of microseismic activity; (b) Generation period of large event; (c) Development period of microseismic activities (modified from Ref. [87])

microseismic events were clustered in the contact zone and a shear band occurred in the seismic event clustered area.

4 Application of microseismic monitoring for other typical hazards

Besides the safety monitoring and assessment of mining process, microseismic technology has also been widely applied for many other aspects in metal mines in China. Many dangerous sources are often encountered during underground mining. For example, the caving and rock strata movement induced by the presence of large scale goaf has become a serious problem demanding prompt solution in some mines, and the fault slip and water inrush pose a serious threat to underground mining. In addition, illegal mining and personnel location have been monitored by microseismic technology in some mines. Therefore, the application of microseismic monitoring technology is widespread due to the complexity of geological conditions and mining environments in underground metal mines in China.

4.1 Microseismic monitoring for goaf stability and rock strata movement

Many untreated goafs, caused by illegal or unplanned mining process, exist in metal mines in China. These goafs in or around underground mines can easily result in the caving or rock strata movement, which seriously threatens deep mining [88]. Statistically, there are more than 1.28 Gm^3 of goafs distributed in 28 provinces (cities and districts) in China [89]. Large scale goafs can lead to large-area caving, rock strata movement, ground surface subsidence, serious waste of mineral resources, environmental degradation, local stress concentration, and even rockburst. Therefore, microseismic technology has been applied to monitor the rock mass fracture process near the goaf in many metal mines [90−92]. By conducting microseismic monitoring in Panluo iron mine, WANG [93] established the stability assessment method of rock mass near the goaf by analyzing the spatial and temporal distribution of microseismic events (Figure 16). In Dahongshan iron mine, a

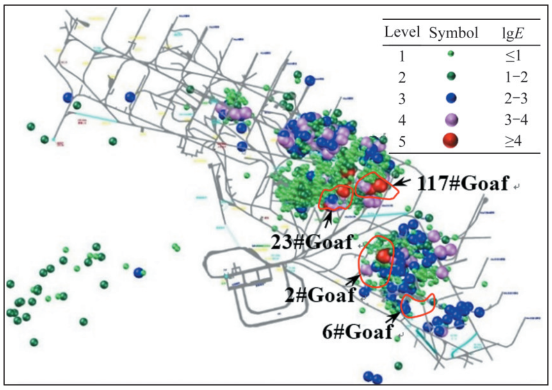


Figure 16 Spatial distribution of microseismic events near goaf in Panluo iron mine (modified from Ref. [93])

bulky mining-out area was formed with sublevel caving method. Based on the precise location of fracture source with multi-channel microseismic monitoring technology, LI et al [94] studied and deduced the high-stress concentration zone, its developing trend and the outer boundary of the goaf. Finally, the caving zone and cracking zone in overburden in different periods were obtained, as shown in Figure 17.

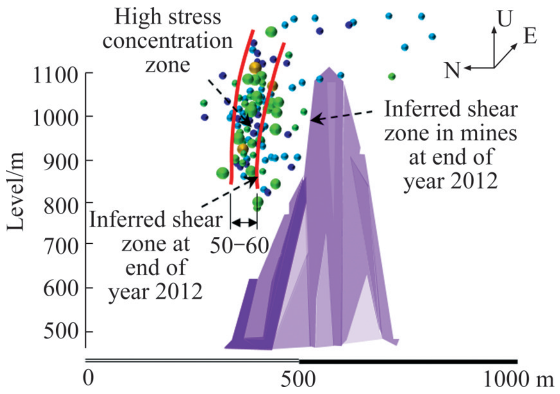


Figure 17 Expansion process of high stress concentration zone using microseismic monitoring in overburden in Dahongshan iron mine (modified from Ref. [94]) (Note: Local Cartesian coordinates coordinate system was adopted; E, N and U represent east, north, and up, respectively.)

4.2 Microseismic activities induced by fault slip

Fault, as a special medium different from intact rock mass [95], breaks the continuity and integrity of rock mass. The strong disturbances from blasting and unloading during large-scale mining probably induce fault activation and slippage, resulting in the occurrence of ground pressure hazards in tunnel and stope near the fault. ZHANG et al [96] used microseismic technology to monitor the fault activity near the No. 6 huge goaf and the stability of wall rock mass of the mined-out areas in Shouwangfen Mine. The location of fault activation was obtained based on the analysis of microseismic activities. Based on temporal and spatial distribution of microseismic events and deformation mechanism, ZHANG et al [97] found that the propagation of the buried fault F15 caused the failure of the crown pillar. By analyzing the temporal changes in multiple microseismic parameters during the fracture process of the crown pillar, it was found that several distinct abnormalities in the microseismic data, such as a rapid decrease in the b value, a sharp increase in energy release, an abnormal increase in apparent stress and a low dominant frequency, could be judged as the signal of an increasing risk. XIE [98] conducted a study on the microseismic activity and rock stability near the fault in Piaotang tungsten-tin mine as shown in Figure 18. The study established a correlation between blasting process vs energy index and Schmidt number. From the distribution of displacement and $\lg I_{\mathrm{E}}$, LIU et al [99] found that microseismic events were mainly concentrated at footwall of the fault under the disturbance of mining process, as shown in Figure 19. When the distance to fault exceeded 20 m, rock mass remained relatively stable.

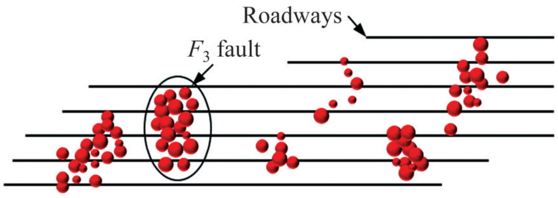


Figure 18 Spatial distribution of microseismic events near the fault of the Piaotang tungsten-tin mine (modified from Ref. [98])

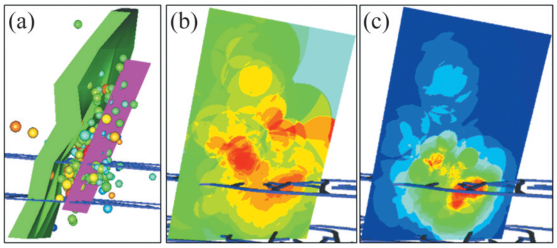


Figure 19 Contour map of stress and deformation near fault in Hongtoushan copper mine: (a) Profile of fault; (b) Contour map of stress; (c) Contour map of deformation (modified from Ref. [99])

4.3 Monitoring for hazards induced by groundwater

Water inrush is another typical hazard in underground mines, and becomes increasingly serious with an increased mining depth. The change in permeability of surrounding rock mass contributes to water inrush from roofs, fracture zones and floors. Sanshandao gold mine, the only submarine gold mine in China, faces challenges of fragmentation of surrounding rock mass, difficult support, poor stability of hanging wall and high risk of water inrush. BI et al [100] performed online microseismic monitoring for the mining process and fault slip under the sea in Sanshandao gold mine and considered that the microseismic technology provides a powerful support to the assessment and warning for the risk of groundwater inrush (Figure 20). For another typical mine with high risk of underground water inrush, Zhangmatun iron mine, LIU et al [101] performed an analysis by using microseismic monitoring and numerical simulation and found that the original stress field was greatly changed under high water pressure and mining disturbance. The study delineated the accumulated three-dimensional spaces of micro-ruptures, and divided the possible dangerous water inrush regions of grout curtain, as shown in Figure 21.

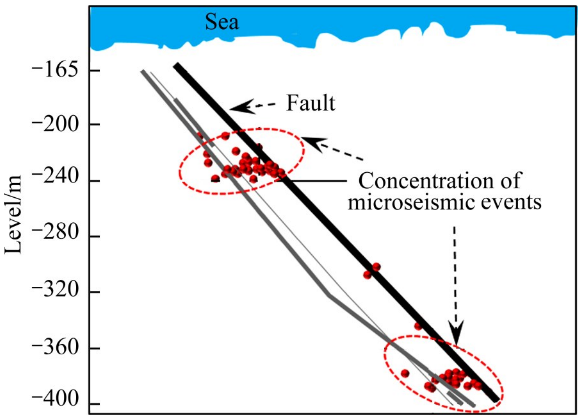


Figure 20 Distribution of microseismic events under sea in Sanshandao gold mine (modified from Ref. [100])

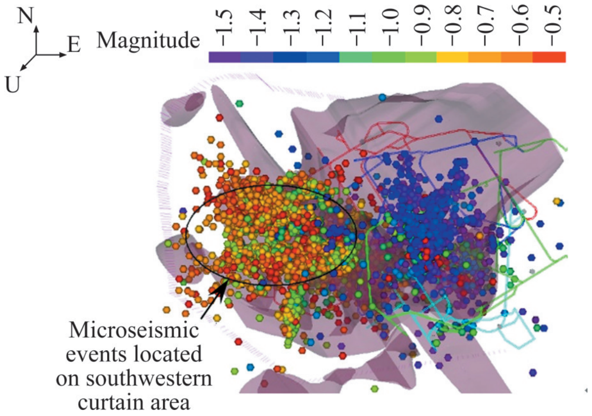


Figure 21 Top view of microseismic events in Zhangmatun iron mine (modified from Ref. [101])

Besides the underground water, rainfall also influences the rock mass stability. Aiming at the influence of rainfall permeation on stope stability, PENG et al [102] quantitatively analyzed a typical case of stope collapse and the law of ground pressure activity influenced by rainfall permeation. The result indicated that the ground pressure activity increased with an increase in rainfall as shown in Figure 22. This suggests that rainfall permeation is an important cause of stope instability.

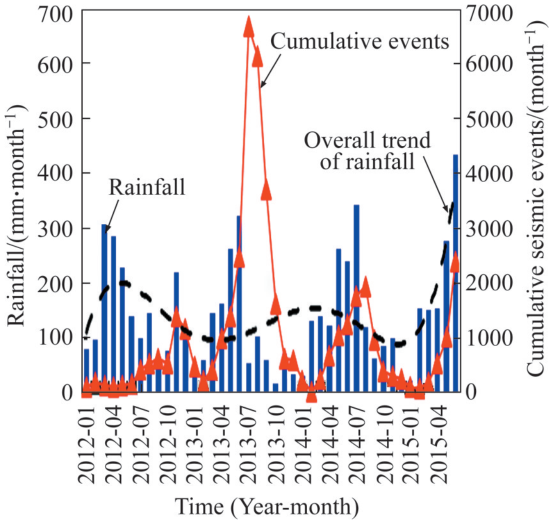


Figure 22 Variation trend of microseismic events with rainfall in Xianglushan tungsten mine (modified from Ref. [102])

4.4 Personnel location and rescue

As per the Chinese government regulation, personnel positioning system must be installed in all the underground mines to improve the efficiency of emergency rescue work. When an accident occurs, rescuers can keep abreast of the personnel and equipment information by receiving the distress signal released by personnel based on the positioning system. As the microseismic technology can continuously monitor vibration signal in real-time, it can provide an effective supplement to the process of underground rescue work. LIU et al [103] designed a test program to simulate mine disaster rescue to verify the usability of microseismic monitoring systems in rescue work. The optimal distances for different sound signals to be received by the microseismic system were studied. The results showed that the clarity of signals received by the microseismic system followed a sequence of tapping anchor>tapping rock>tapping conduit>shouting and the optimum distances for taking the four kinds of actions were obtained, as shown in Figure 23.

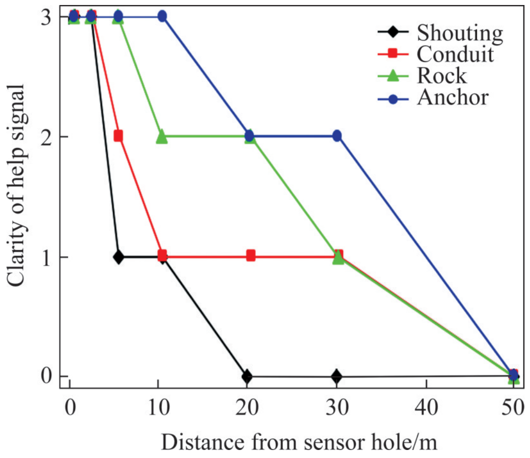


Figure 23 Relationship of distance vs sound clarity of received signals detected by microseismic system (modified from Ref. [103])

4.5 Monitoring for illegal mining

The problem of illegal mining in some metal mines is a threat to mine workers due to the possibility of encountering unknown goafs caused by illegal mining. Moreover, illegal mining causes wastage of mineral resource for no economic benefit to the nation. Hence, it is necessary to monitor and prevent these mining behaviors in real-time. Based on the microseismic technology, illegal mining was monitored and accurately located in Shirengou iron mine by NAN et al [104], which effectively reduced the behaviors of illegal mining. ZHANG et al [105] introduced spatial clustering methodology into the analysis of microseismic data, which effectively reduced the difficulty of catching illegal mining activities by grouping the blasting events with similar characteristics. A typical blasting event from illegal mining identified by this method is shown in Figure 24.

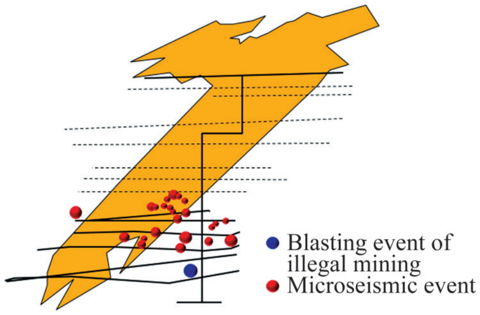


Figure 24 Distribution of microseismic events and blasting event by illegal mining (modified from Ref. [105])

5 Prospect of microseismic technology in underground metal mines in China

Some typical characteristics gradually emerge with an increase in the depth and scale of mining in metal mines, including:

1) High stress conditions, especially the tectonic stress that could reach tens or even hundreds of MPa;

2) Orebody shape and orebody occurrence are irregular;

3) Large mines involve complex spatial tunnels arranged in tens of kilometers horizontally and several kilometers vertically;

4) Strong disturbances are caused by unloading effect and blasting. For example, the ore production in a single stope can reach 10^5 m^3. The maximum explosive usage of one blasting can reach several tons and the blasting processes are often performed in tens of stopes simultaneously.

Due to the complexity of engineering layout and the strong disturbances, the ground pressure hazards in underground metals mines are much more complex than those in either coal mines with layered structure using mechanized operation or tunnel engineering with linear structure using smaller blasting charges. The complexity of hazards in underground metals mines are as follows:

1) The hazards possibly widespread in all underground components, including stope, roadway and shaft;

2) Ground pressure hazards can have diverse forms including spalling, caving and rockburst;

3) The causes of hazards are more complex, e. g., energy accumulation by high stress and rapid release, hazards controlled by fault slip, and hazards induced by mining disturbance.

Although microseismic technology has gradually become a primary method for safety monitoring and management of deep mines in the last two decades, many key scientific and technical problems are yet to be solved to make the technology more useful in underground metal mines in future.

Because of the complexity of geological conditions and mining process, the extent of utilization of information technology and artificial intelligence in mining engineering is far behind other industries. It is necessary to obtain sufficient data for mining design and theoretical research using advanced testing technologies. Informationization construction is an important part of intelligent mine. Microseismic data can reveal the generation and propagation of cracks in rock mass, which provides useful information for rock mass stability evaluation. In view of that the microseismic data is easy to realize digitization and informatization, microseismic technique will play an increasingly important role in intelligent mines construction. Furthermore, by considering underground mines from the perspective of informatization, automation and intelligentization, future studies should focus on the intelligent microseismic data processing methods, e. g., signal identification of microseismic and precise location algorithm, as well as on the independent research and development of microseismic equipment. Integrated monitoring and collaborative analysis for rock mass response caused by mining disturbance also have extensive prospects for development.

5.1 Intelligent analysis of microseismic data

The accuracy of source location, which is affected by many factors, is the core element in the application of microseismic monitoring technology. As the P-wave can be easily recorded and its arrival time can be accurately determined, it is recommended to use P-waves in the location algorithms for calculating seismic source position. The location algorithms including least square method [106], Geiger algorithm [107, 108], simplex algorithms [109, 110], and Newton iteration algorithms [111] have been widely applied to the microseismic technology. In addition, important progress has been made by many researchers towards combined location algorithm, i. e., more than two basic algorithms are combined with focus on algorithms that do not need to measure the wave velocity or do not need to pick up P-wave arrival time of the signal [108, 112−122]. With increasingly extensive intersection of disciplines, many new algorithms have been introduced into the source location including genetic algorithm, particle swarm optimization algorithm, and simulated annealing algorithm. CHENG et al [123, 124] systematically summarized the research progress in location algorithm of microseismic events, and proposed a development direction for future research.

The signals generated from rock mass fracture are often mixed with various kinds of noise caused by mechanical vibration, human activities, electrical equipment and blasting process. These noisy signals should be identified and filtered before processing the microseismic data. In recent years, the rapid development of artificial intelligence provides a new direction for the identification of microseismic signal and its source location. The artificial intelligence algorithm can improve the signal-to-noise ratio of seismic data, which is meaningful to the identification of the real microseismic signals [125−127], and the relevant work has been conducted by XIAO et al [128], as shown in Figure 25.

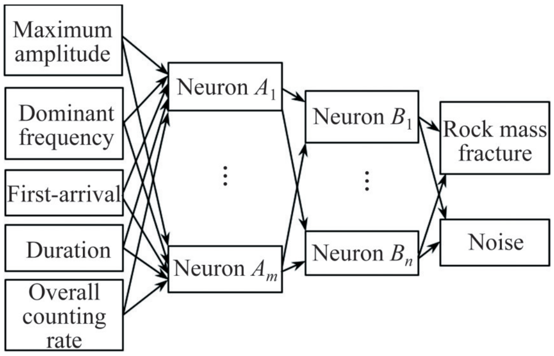


Figure 25 Procedure of identification of MS signals generated from rock mass fracture by neural network method [128]

Microseismic data is vast because the signals are continuously collected by many sensors for a long period, e. g., maybe several years. Moreover, each signal contains many parameters such as amplitude, frequency, and duration. These huge data can be effectively analyzed by the information fusion technology. This technology correlates and synthesizes the data and information from a single source or multiple sources under certain criteria, making a deeper interpretation of the microseismic data [120]. In future, new methods of intelligent algorithm, information fusion technology and big data analysis method will play important role in microseismic data processing.

5.2 Research and development of microseismic equipment

Microseismic monitoring technology has been applied in hundreds of underground mines to monitor rock mass fracture and risk management of ground pressure hazards sine 1980s. Owing to better system stability, high sensitivity and strong post-processing analysis function, the microseismic systems developed by IMS corporation of South Africa, ESG corporation of Canada and SOS corporation of Poland, dominantly occupy the microseismic equipment market. In general, the data processing methods of these systems adopt the concept of closed system, thus users are unable to extend the capability of these microseismic equipments. Consequently, some of the latest research results cannot be embedded in these systems. In recent years, research and development of microseismic equipment has gradually attracted attention in China, and extensive studies have been conducted by some research institutions, including the Institute of Geology of China Earthquake Administration, Institute of Rock and Soil Mechanics of Chinese Academy of Sciences, Northeastern University, Central South University, University of Science and Technology Beijing, Shandong University of Science and Technology, Dalian University of Technology, Liaoning Technical University, and BGRIMM Technology Group.

The mining condition in China is complex. The presence of a large number of noise sources requires the microseismic system to have strict requirements in terms of long-term stability, high sensitivity for detecting weak signal, strong anti-interference ability to various electrical equipment, high accuracy of time synchronization over long distance networks, advanced signal analysis and processing technology, and high accuracy of source location algorithm. The microseismic systems currently available in the domestic and overseas market cannot meet these requirements. Therefore, a good prospect appears in introducing the new theories and new technologies, e. g., the 5th generation wireless systems, anti-interference electronic components, intelligent algorithms and big data analysis method, into the research and development of microseismic equipment.

5.3 Integrated monitoring and analysis for multi-source information during rock mass fracturing

The same as other monitoring methods, the microseismic technology has some limitations when monitoring the initiation and propagation of cracks inside rock mass, including: 1) a large number of tunnels and mined-out area in metal mines that could change the waveforms and its propagation velocity, which will cause inaccuracy in the seismic source location and parameters; 2) limited by the response frequency of sensors and the monitoring cost, weak signals generated from small scale cracks cannot be acquired thereby affecting the reliability of risk assessment; and 3) the results obtained from microseismic technology should be verified with monitoring results from other methods to ensure the accuracy of monitoring results.

The rock mass response information during deep mining process varies widely, and it mainly consists of the structural information such as faults and primary joints; the stress information including in-situ stress and disturbed stress; the deformation information such as rock strata movement, convergence deformation and inner deformation; the cracking information, i. e., the initiation and propagation of new cracks; the vibration information induced blasting, mining machinery and human activity; and the energy information released by rock mass failure. Only part of these information can be monitored by microseismic technology. Therefore, it is recommended that integrated monitoring technologies should be adopted for deep mining as far as the monitoring costs allow. Moreover, the stress, deformation and damage field obtained from numerical simulation provide rich information to the collaborative analysis of rock mass stability. For newly-built mines, it is recommended to establish a long-term monitoring database of various information from the stage of infrastructure construction to provide data support during the entire mining process.

5.4 Intelligent risk assessment and warning for ground pressure hazards

The research institutions including Laurentian

University of Canada, the Institute of Mine Seismology of South Africa and the Commonwealth Scientific and Industrial Research Organization have conducted research on the rockburst control since long ago, and have published many papers and books, such as “Support of underground excavations in hard rock” and “Rockburst support”. However, these research achievements are inadequate in deep metal mines of China due to the complex geological conditions and mining methods. Hence, it is necessary to establish ground pressure disaster prevention and control standards that are applicable to the deep mining conditions in China.

Since the end of the last century, extensive studies have been done in China regarding rockburst mechanism and its control methods. A typical comprehensive research on rockburst was conducted by FENG et al [20] based on thousand plus rockbursts occurred in the deep tunnel in Jinping II Hydropower Station. The study combined the use of rock mechanics experiment, physical modeling experiment, in-situ integrated monitoring and numerical simulation. Consequently, many new findings were obtained, including the mechanism of different types of rockbursts induced by different construction methods and the quantitative warning methods for rockburst regions and grades based on microseismic data. Control procedure for different types of rockburst were also obtained including optimized construction design, stress relief measures, energy absorbing supports and dynamic control methods, as shown in Figure 26. Nevertheless, these research achievements were obtained for a tunnel, i. e., a linear underground structure, and the extension of these achievements for rockburst control in deep mining process will be essential.

Up to now, no substantive progress has been made in intelligent management, warning and control procedure for ground pressure hazards, especially for rockburst in deep metal mines in China. Therefore, it is necessary to establish an extensive database of ground pressure hazards and in-situ integrated monitoring information by collecting information from metal mines. Then, studies on the quantitative relationship between the occurrence process of different types of hazards vs geological environment, stress condition, mining sequence, blasting parameters, rock mass failure information, etc., should be performed to reveal the precursor characteristics of multiple monitoring information before hazards actually occur. Finally, it is recommended to establish an intelligent prediction model for ground pressure hazards by using advanced analytical methods such as the artificial neural network deep learning and the big data analysis method. The model can significantly promote the intelligent management level of ground pressure hazards in deep metal mines.

6 Conclusions

Under high ground stress conditions in deep metal mines, frequent and strong mining disturbances can easily lead to spalling and collapse of the surrounding rock mass, even generating dynamic hazards such as rockburst. Microseismic monitoring technology has become an effective tool for the evaluation of rock mass stability and warning of dynamic disasters and will play an important role in deep metal mines in China. This paper reviews the literature regarding the use of microseismic technology in deep metal mines in China and obtained the following conclusions.

1) Since microseismic signals are generated by the propagation and expansion of cracks, each microseismic signal contains plentiful information of the structural changes inside the rock mass. Compared to the traditional test methods for stress and deformation that can obtain only the point, line or surface information, microseismic technology can provide three-dimensional information of changes in stress and deformation inside rock mass in real time, and are extremely helpful to the engineering design and research of rock mass mechanics. At present, microseismic monitoring system has been employed by more than 40 underground metal mines in China.

2) The application of microseismic monitoring technology is widespread in metal mines. The changes in their microseismic parameters have been widely applied to evaluate the rock mass stability, identify the potential region of hazards, and make qualitative or quantitative warning for the dynamic

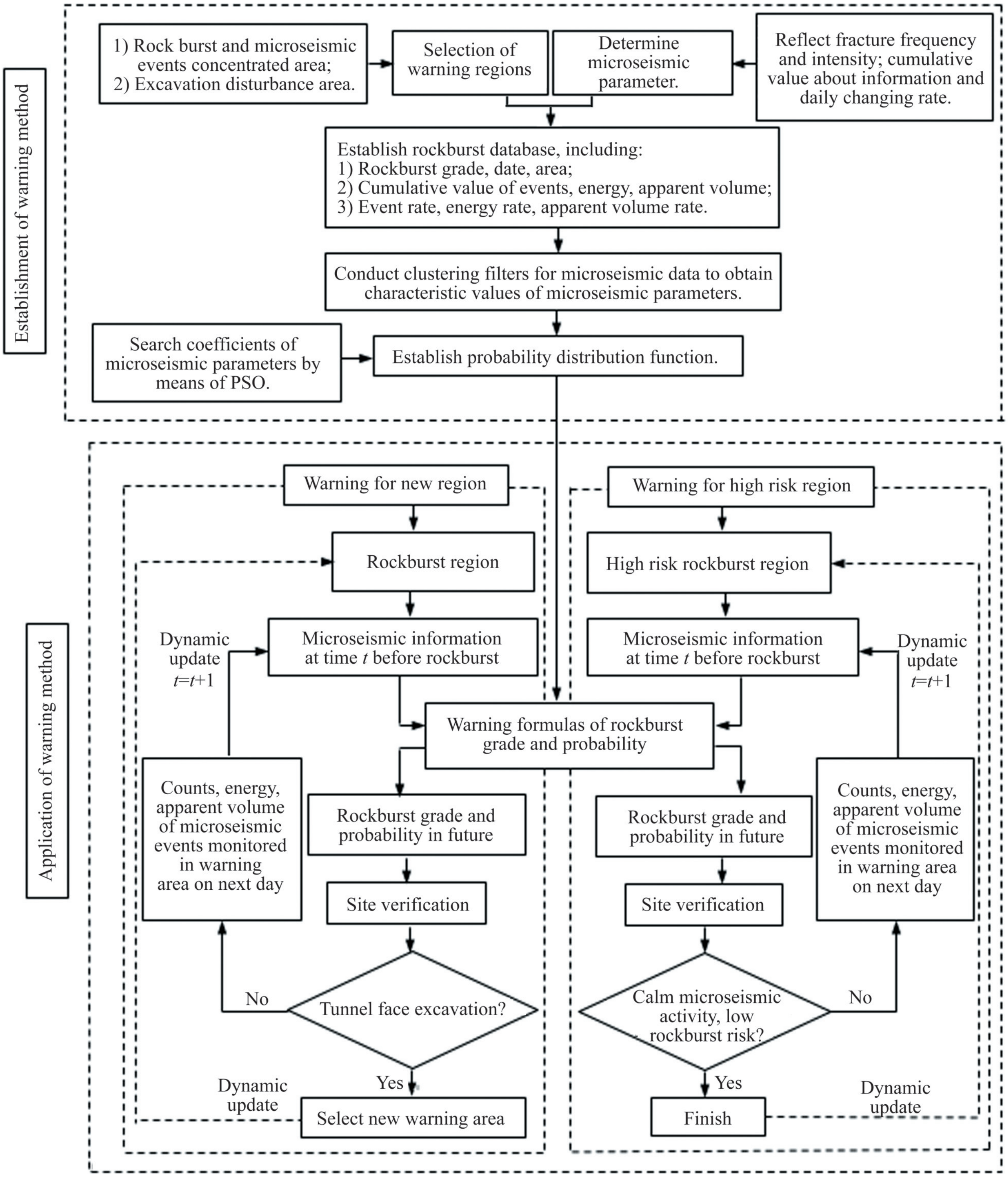


Figure 26 Dynamic procedure for warning and controlling rockburst in deep buried tunnel based on evolution of microseismic information (modified from Ref. [20])

disasters induced by mining process, blasting, water inrush and large scale goaf. The stress and deformation obtained from microseismic data can also be used to evaluate the accuracy of mining process, to optimize mining parameters, and then to realize dynamic control of mining process. Moreover, it is also used to monitor illegal mining, which can also be utilized as an effective supplement in the rescue work during underground hazards. The cracking mechanism as revealed by microseismic monitoring has gained widespread research attention and it has been utilized to optimize rock mass support parameters.

3) Although the microseismic technology has gradually become a primary method for safety monitoring and management in the last two decades, many key scientific and technical problems are yet to be solved for the technology to play an important role in underground metal mines in China. Considering underground mines from the perspective of informatization, automation and intelligentization, studies should be focused on intelligent microseismic data processing method, e.g., signal identification of microseismic and precise location algorithm, as well as on the independent research and development of microseismic equipment. Integrated monitoring and collaborative analysis for rock mass response caused by mining disturbance also have extensive prospects for future development in the field of microseismic technology.

Contributors

LIU Jian-po put forward the concept and wrote the original draft of the manuscript. SI Ying-tao conducted the literature review and edited the manuscript. WEI Deng-cheng, SHI Hong-xu and WANG Ren collected the related references and drew the pictures inside the paper.

Conflict of interest

LIU Jian-po, SI Ying-tao, WEI Deng-cheng, SHI Hong-xu and WANG Ren declare that they have no conflict of interest.

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中文导读

中国地下金属矿山微震监测技术应用进展及展望

摘要：微震监测技术已经成为我国地下金属矿山岩体安全风险管理的重要技术手段。我国金属矿具有构造应力大、矿体形态不规则、矿体赋存条件多样、生产工序复杂的特点，相对于国外矿山及其他地下工程领域，微震监测技术在我国地下金属矿山的应用具有多样性。本文系统总结了我国地下金属矿山微震监测应用现状、应用领域及取得的相关成果，覆盖地压灾害监测与安全风险评估、回采参数优化、岩体破裂机制、采空区稳定性监测、断层滑动风险评估、矿山救援人员定位、民采盗采监测及水害造成的岩体稳定性监测等方面。此外，结合我国金属矿山开采领域信息化、无人化、智能化的发展需求，提出了我国微震监测技术在信号智能识别及精确定位算法、设备自主研发、与其他开采扰动岩体响应信息协同分析和地压灾害风险评估应用等方面的信息化、智能化发展方向。

关键词：地下金属矿山；微震；安全管理；岩体稳定性；灾害预警；综合监测