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Preliminary engineering application of microseismic monitoring technique to rockburst prediction in tunneling of Jinping II project

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Abstract: Monitoring and prediction of rockburst remain to be worldwide challenges in geotechnical engineering. In hydropower, transportation and other engineering fields in China, more deep, long and large tunnels have been under construction in recent years and underground caverns are more evidently featured by "long, large, deep and in group", which bring in many problems associated with rock mechanics problems at great depth, especially rockburst. Rockbursts lead to damages to not only underground structures and equipments but also personnel safety. It has been a major technical bottleneck in future deep underground engineering in China. In this paper, compared with earthquake prediction, the feasibility in principle of monitoring and prediction of rockbursts is discussed, considering the source zones, development cycle and scale. The authors think the feasibility of rockburst prediction can be understood in three aspects: (1) the heterogeneity of rock is the main reason for the existence of rockburst precursors; (2) deformation localization is the intrinsic cause of rockburst; and (3) the interaction between target rock mass and its surrounding rock mass is the external cause of rockburst. As an engineering practice, the application of microseismic monitoring techniques during tunnel construction of Jinping II Hydropower Station was reported. It is found that precursory microcracking exists prior to most rockbursts, which could be captured by the microseismic monitoring system. The stress concentration is evident near structural discontinuities (such as faults or joints), which shall be the focus of rockburst monitoring. It is concluded that, by integrating the microseismic monitoring and the rock failure process simulation, the feasibility of rockburst prediction is expected to be enhanced.

Key words: microseismic monitoring; numerical modeling; rockburst; prediction

1 Progress in monitoring and prediction of rockburst

In hydropower, transportation and other engineering fields in China, a growing number of deep, long and large tunnels have been under construction in recent years. Underground caverns are more evidently featured by "long, large, deep and in group". It leads to many problems associated with rock mechanics problems at great depth, with rockburst as the most prominent one. Rockburst not only undermines underground structures and damages equipments, but also presents serious threats to personnel safety. It has become a major technical bottleneck in future deep underground engineering in China [1–11].

Rockburst is a catastrophic phenomenon triggered by a progressive failure process of rocks, which has extremely complex mechanical mechanisms. The present studies are mostly based on hypotheses or experiences. As noted by Brown [12], it is difficult even to reach a consensus on the definition of rockburst. The accurate response to the problem of rockburst is currently under study by many researches. Its progress stands for the development and a major breakthrough in rock mechanics. Hoek and Brown [13] also pointed out that this type of progressive failure process was still not clearly understood up to now.

Rockburst occurs frequently in South Africa, mainly in gold mines. Consequently, South Africa is among the first few countries that carry out systematic and long-term researches on rockburst. Within ten years,

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the number of rockburst accidents in South Africa increased from 7 times in 1908 to 233 times in 1918. Only in 1975, 680 rockburst events took place in 31 gold mines in South Africa, which claimed a death toll of 73 and a loss of 4 800 production shifts. In December 1976, a rockburst with a magnitude of M_L = 5.1 occurred in Welkom, Free State, South Africa, which led to a collapse of a six-storey surface building. Almost all the gold mines in South Africa are under the threat of rockburst hazards without exception.

During construction of the Simplon Hydraulic Tunnel in the Alps region, the overburden depth was greater than 2 200 m. Rockburst and plastic flow phenomena caused by initial rock stresses occurred more intensively and regularly with increasing depth [14]. Rockburst took place during construction of the middle portion of the Shimizu Tunnel in Japan at a depth of 1 000–1 300 m. When the Shin-Shimizu Tunnel was excavated in 1966, rockburst occurred again at a depth slightly shallower than the previous one. The sizes of the ejected rock blocks ranged from tens of centimeters to one or two meters and the thickness from 10 to 30 cm. The Kanestu Tunnel was constructed mainly in quartz diorite and the overburden depth was generally 730–1 050 m. Most rockbursts occurred at working faces after blasting and none occurred at the sidewalls.

The Ruhr mining area was a coal field with the largest coal yield in Germany. It experienced the earliest coal bursts, and 283 hazardous rockbursts were recorded from 1910 to 1978 [14]. Tashtagol Iron Mine in the former Soviet Union was one of the fields exposed to the extremely dangerous rockburst hazards. Rubin Copper Mine in Poland was a hard rock mine with most frequent rockburst events. The rockburst in Galena Mine in the United States was classified as pillar burst. The lead, zinc and silver mines in Coeur d'Alene, north Idaho, the United States, are currently suffering from severe rockburst hazards. Since the 1980s, rockbursts have occurred in a number of copper and nickel mines in Sudbury, Canada. The most representative one was Makassar Gold Mine in the Kirkland Lake area, Ontario.

El Teniente Copper Mine in Chile experienced a rockburst in March 1992, which resulted in a collapse of more than hundreds of meters of laneway and cease of production for 22 months. It was the most severe rockburst in South America [14]. In the 1960s, a road tunnel in Norway and a headrace tunnel in Sweden were typical cases of rockbursts in tunnel. The locations of rockbursts were symmetrical with respect to the tunnel axis and the sound induced by the most violent rockburst was equivalent to a blast of 200 kg dynamite. Two accessory hydraulic tunnels of Forsmark Nuclear Plant in Sweden were constructed in granite gneiss at a depth of 5–15 m. Rock fragments were ejected by rockburst with sizes of about 10 cm×10 cm and crackling. The Ritsem Traffic Tunnel in Sweden was excavated in mylonite at an overburden depth of 130 m. The rockburst in this tunnel was split-burst.

The earliest coal burst on record in China took place in Shengli Mine, Fushun in 1933 [14]. According to incomplete statistics, over 2 000 coal bursts happened in 33 mines in China during 1949–1997, which led to death or injury of a few hundred people and cease of production for more than 1 300 days. The headrace tunnel of Yuzixi I Hydropower Station on Minjiang River was excavated in granodiorite and diorite at a depth of 250–260 m and had a total length of 8 429 m. Over ten rockburst events occurred intermittently within a distance of 6 km along the tunnel, with intervals of 1–25 m, generally 10 m on average. Rockbursts occurred most intensively within 24 hours after the working face was excavated and usually lasted for 1–2 months. For some sections, rockbursts were detected even after the tunnel was excavated for one year.

A number of rockburst events occurred during construction of the headrace tunnel (ϕ 10 m) of Tianshengqiao II Hydropower Station on Nanpanjiang River and continued for two months [14]. The surrounding rock was composed of thick massive limestone and dolomite. The cover depth was 120–160 m. Most rockbursts occurred at the sidewalls, 4–10 m away from the working face. The area of sporadic rockbursts regions ranged from 0.5 m × 0.5 m to 2.0 m × 2.0 m. Extensive rockbursts happened in an area with a width of 3–4 m and a length of 10–20 m along the longitudinal tunnel axis. The ranges for continuous rockbursts were 2–3 m wide, more than 10 m long and extended for 100–150 m.

The Erlangshan Tunnel in Sichuan—Tibet Highway was excavated in sandy mudstone, marl and quartzite. The maximum cover depth was 770 m. More than 200 rockburst events occurred at a depth of 270–570 m. Rockbursts happened most frequently within the zone between the working face and the location three times of tunnel diameter away. Most rockbursts occurred at the tunnel sidewalls, spandrel and vault. The Dongguashan Copper Mine was a hard-rock metal mine with the largest mining depth in the 1990s in China. The main mining depth was 800–1 000 m below ground surface. A number of rock ejection phenomena were observed during construction of roadway infrastructures [15]. Rockbursts occurred at a depth of 790–850 m. At the cover depth of 850 m, rockbursts occurred at the sidewalls and the roof composed of skarn. The crackling sound lasted for about 20 days, and the rock bolt and mesh support were damaged. At the cover depth of 790 m, rockbursts again took place in skarn. After installation of rock bolt and mesh support, the rock bolts were destroyed by shear and 1.8 m-long floor heave appeared.

The Qinling Railway Tunnel was excavated in mixed granite and gneiss with a maximum overburden depth of 1 600 m. During tunnel construction, four sections experienced intensive rockbursts at the depth of more than 900 m [16]. Rockbursts occurred over an accumulated length of 1 900 m, among which the four sections occupied 600 m. The Cangling Tunnel in the Taizhou—Jiyun Highway in Zhejiang Province was constructed in tuff, with a maximum cover depth of 768 m. Rockbursts generally occurred between the working face and the position 1–2 times of tunnel diameter away. Rockburst events were frequent within 12 hours after excavation and mainly took place at the sidewalls and some near the vault [17]. The underground powerhouse of Pubugou Hydropower Station was located in granite on the left bank. A number of rockbursts occurred during excavation. Most rockbursts took place near the upper corner of the upstream sidewall [18].

The auxiliary tunnel (east end) of Jinping II Hydropower Station was excavated in marble. Rockbursts took place in the sections more than 2 000 m below ground surface. Most rockbursts occurred near the newly excavated working face, generally on the tunnel vault and haunch. Rockbursts were mainly observed near the intersections between the cross passage and the main tunnel, irregular cross sections and enlarged sections. The maximum size of ejected rock blocks was 4.0 m × 2.0 m × 1.5 m (length × width × height).

The Lujialing Tunnel along Chongqing—Yichang Highway was excavated in tuff at a cover depth of 120–600 m. Rockbursts occurred most frequently at the upper corners and sidewalls 0.5–1.0 time of tunnel diameter away from the working face. 93 rockburst events were recorded and most happened within 24 hours after excavation of the working face.

At present, many rockburst theories were proposed, using mainly the strength theory, the energy theory, the burst liability theory, the stiffness theory and the instability theory. Chinese researchers including Tang et al. [19–26] have conducted a lot of studies on rockburst mechanism by using the catastrophe theory. In addition, Chinese scholars also applied the bifurcation theory, the theory of dissipative structures, the theory of chaos to the studies of deformation localization and stability of the mechanical system in rock, and promoted the development of theories on rockbursts and rock instability. Xie and Pariseau [4] investigated the rockburst mechanism and prediction methods based on fractal geometry. Tan [27] proposed a comprehensive evaluation method for rockburst prediction based on fuzzy mathematics. Ge and Lu [28] conducted numerical simulations on rockburst behavior by the discontinuous deformation analysis (DDA) method. For tunnels excavated in brittle rocks, fracture of surrounding rocks and ejection of rock fragments can be reasonably simulated. Recently, in terms of rockburst prediction, Yang and Zhu [29] proposed an extenics evaluation method; Feng and Wang [30] presented a method based on artificial neural network; Jiang et al. [31] put forward an application of grey system optimal theory model; Feng and Zhao [32] presented a rockburst classification method based on support vector machines (SVMs); Gong and Li [33] applied the discriminant analysis method to rockburst prediction. These studies offered new ideas and approaches for rockburst prediction.

Lately, Zhang et al. [14] tried to establish five factors comprehensive criterion for strain-mode rockburst and its classification. As recognized that occurrence of rockburst is caused and revealed by multiple factors but not one or two, as shown in Table 1, this latest comprehensive criterion and its classification were proposed based on conventional criteria and classification methods existing domestically and internationally. It was also extracted from domestic engineering experiences.

Table 1 Rockburst criterion and its classification based on five factors comprehensive studies.

Rockburst classification	σ_1/R_c	σ_θ/R_c	σ_c/R_t	W_{et}	K_V
No rockburst	< 0.15	< 0.20	< 15	< 2	< 0.55
Slight rockburst	0.15–0.20	0.20–0.30	15–18	2.0–3.5	0.55–0.60
Moderate rockburst	0.20–0.40	0.30–0.55	18–22	3.5–5.0	0.60–0.80
Strong rockburst	> 0.40	> 0.55	> 22	> 5	> 0.80

Many existing studies attempted to monitor and predict rockburst events, including the microgravity method, the rheologic method, the rebound method, the drilling-yield method, the microseismic method, and so on [4]. Although all of these methods have been used, none is proved to be adequately reliable, and almost no successful application has been reported. One of innovative ideas is to combine comprehensive criteria and classification studies with experiment, simulation and microseismic monitoring. This is expected to be tested in practice.

Monitoring and prediction of rockbursts have been recognized as challenging tasks worldwide. It is usually considered that, similar to earthquakes, the seismic source of rockburst is dominated by shear rupture and rockburst has scale invariant properties. In other words, no essential difference in physical nature is observed between rockbursts and earthquakes. Therefore, many researchers conclude that the low success rate of earthquake prediction indicates the dim future of rockburst prediction. Experts in rock engineering further doubt whether rockbursts can be forecasted due to the consecutive occurrence of a number of unpredicted earthquakes in recent years. The low success rate of earthquake prediction has greatly affected the confidence in rockburst monitoring and prediction in the rock engineering field.

In recent years, as a three-dimensional monitoring technique for microcracking in rock, the microseismic monitoring technique has been developed rapidly. The microseismic monitoring technique can be used not only to obtain the three elements of time, location and magnitude by acoustic analysis, but also to capture the precursory information about microcracking in rock, which has a magnitude less than that of rockburst if a high-sensitivity microseismic monitoring system is employed. Thus, it is potentially possible to predict rockbursts. Currently, advanced rockburst monitoring network systems have been established for many deep mines in Canada, the United Sates, South Africa and Australia. In China, several sets of monitoring equipments were imported by a few large coal mines and metal mines. However, the application is far less prevalent due to high costs. In addition to costs, another key problem restricting the application of microseismic monitoring system in hydraulic and transportation engineering in China is that no successful case of rockburst prediction has been reported. Since the study of rockbursts is still in the exploratory stage, in-depth understanding on initiation and development of rockbursts is absent, and many aspects on rockburst mechanism are still unclear. With various monitoring data, the problems how to sufficiently utilize and reasonably interpret the first-hand data and identify the information useful for rockburst prediction have become difficult tasks in rockburst monitoring and prediction. Therefore, strengthening the researches on analysis methods and monitoring techniques for rockbursts is of theoretical and practical significance in promoting the technical advances in deep underground engineering in China in the 21st century, preventing hazards triggered by construction of deep underground structures and ensuring the safe construction and operation of deep underground work.

In this study, the microseismic monitoring technique was applied to the tunnel construction of Jinping II Hydropower Station. This paper discusses the feasibility of microseismic monitoring and prediction of rockbursts from three aspects, namely, the mechanical foundation, the monitoring techniques and the engineering practice. The preliminary monitoring results are presented and analyzed.

2 Fundamental mechanical mechanism for rockburst monitoring and prediction

As both rockburst and earthquake involve fracturing and failure processes of rocks, theories of seismology and geophysics are undoubtedly very instructive for researches on rockburst monitoring and prediction. In particular, the studies on microseismic monitoring and location have been precious knowledge for researches on rockbursts.

Despite the mechanical mechanism similar to earthquakes, most rockbursts are caused by human engineering activities compared with natural earthquakes. Due to excavation of caverns, tunnels or laneways, the original stress balance will be broken, which will lead to stress redistribution, sudden increase in local stresses and further concentration of energy. It may further result in deformation localization, trigger microcracking in rocks, and drive the static balance towards a dynamic instability in surrounding rocks. A great amount of elastic energy will be released and thus rockburst will be generated. Compared with natural earthquakes characterized by long cycles of development, low occurrence rate and large focal depth, the seismic source of a rockburst may be accessible (such as at the working face). Rockbursts can take place in a very short period of time and can recur. More important, for a large and long tunnel, the geological structures can be relatively more clearly identified, the occurrence region of rockbursts can then be related to the construction progress and is highly repeatable. Therefore, compared with earthquakes, monitoring and prediction of rockbursts are more feasible in theory. The reasons can be explained in the following three aspects:

(1) Source zones. The occurrence of natural earthquakes is mainly determined by geological conditions and strata structures of the crust. However, the overall internal structure of the crust in a large scope can hardly be identified. Hence, it is very difficult to determine the location of an earthquake. Whereas, for underground construction, in particular tunnel engineering, the geological conditions within the project area are investigated as detailedly as possible. Therefore, engineers can have an overall understanding on the underground engineering structures and the mechanical properties of surrounding rocks. This can provide an important reference for analyzing the causes of rockburst, especially for identifying the correlation between rockbursts and geological structures.

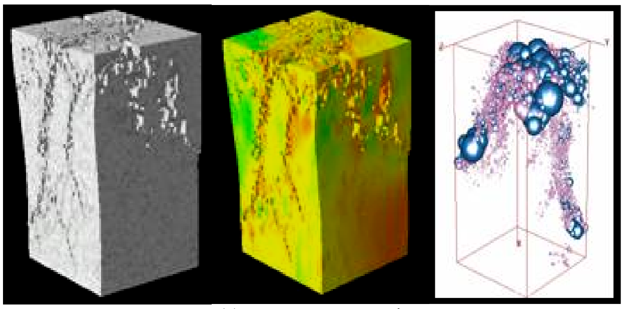
(2) Development cycle. The development cycles of natural earthquakes can be very long, and most of them are more than hundreds of years. A researcher can hardly comprehensively understand the development process and the history of a specific earthquake even in his entire lifetime. Nevertheless, underground engineering such as tunneling is an orderly construction process based on its design. The rockburst events are usually closely related to the known excavation activities (i.e. disturbances). Hence, the development process of rockburst is certainly in relation with the construction process in temporal and spatial sequences. Especially for large and long tunnels, although the construction period may be only a few years, several or even dozens of rockburst events may occur. Most rockbursts follow certain laws and are repeatable. This is favorable for understanding the behaviors of rockbursts and enhancing the feasibility of rockburst prediction.

(3) Scale. seismologists can hardly establish a large-scale geological model for the whole crust. However, due to the current computer technology, in an engineered scale, it is possible to establish a three-dimensional geological model for engineering structures. A three-dimensional model for the overall engineering structure can be built. Analyses of stress field and structural stability can then be carried out for the whole engineering structure and facilitate monitoring and prediction of rockbursts.

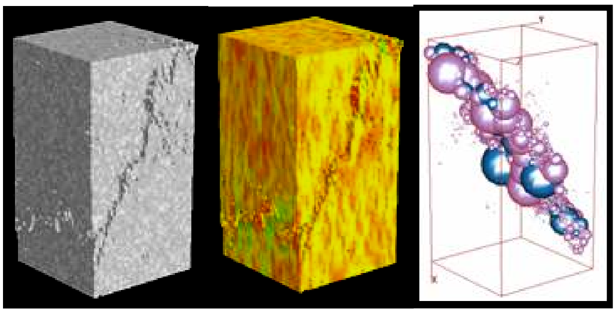
In the authors' opinion, the feasibility of rockburst prediction can be understood in the following aspects:

(1) The heterogeneity of rock is the root for the existence of rockburst precursors. Rock is essentially a heterogeneous material [34, 35]. On a smaller scale, rock is usually composed of various mineral grains, cementing agents and defects like pores. In a larger scale, rock consists of beddings, cracks and other defects. At an even larger scale, it contains faults and other structural features. For stress analyses of an engineering structure, the rock is often simplified as a homogeneous material. However, when the failure process of rock (such as rockbursts) is investigated, if the rock heterogeneity is ignored, many special phenomena related to heterogeneity during rock deformation and failure process may be ignored, for instance, acoustic emission (AE) or microseismic pattern. It can be very difficult to analyze the precursors for rock structure instability and can also be detrimental to monitoring and prediction of rockbursts without consideration of rock heterogeneity. Because of rock heterogeneity, more or less microcracking precursors appear before macro failure of any rock structure, which is the most fundamental mechanical mechanism for the predictability of rockbursts.

Figure 1 shows the failure processes of two rock samples with different homogeneity indices by RFPA modeling. It can be seen that more heterogeneous rock produces more distributed fractures. Figure 2 shows the occurrence of microcracking events with time for four homogeneity indices by RFPA modeling, where m stands for the homogeneity index of rock. The larger the value of m is, the more homogeneous the rock is. The simulation results indicate that higher homogeneity likely leads to more precursory microcracking events and more disorderly distribution of microcracks. Obviously, the rock heterogeneity has great impacts on the precursory patterns for rock failure. In case of m = 5.0, which corresponds to a relatively higher homogeneity, the simulation results indicate that almost no precursory microcracking occurs before macro fracture of rock (the step with the largest number of microseismic events) appears. This shows that the failure of homogeneous medium can hardly be predicted by the precursory microcracking. It is just the opposite in case of m = 1.5. A large number of precursory microcracking



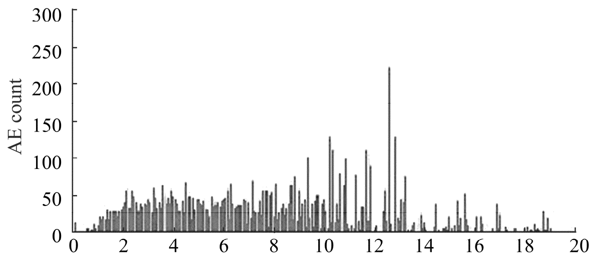
(a) Heterogeneous rock.



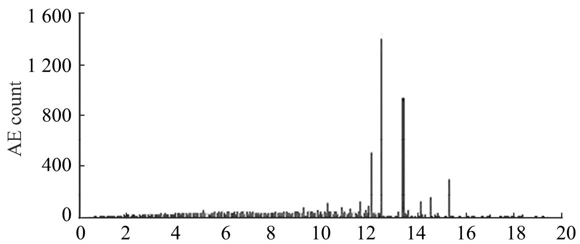
(b) Homogeneous rock.

Fig.1 Effects of rock heterogeneity on failure process (numerical simulation by RFPA).

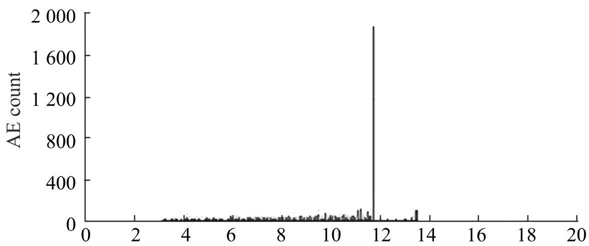
events are detected before macro failure. This indicates that precursors do exist before the macro failure of heterogeneous medium, which is very helpful for predicting instability and failure of heterogeneous medium.



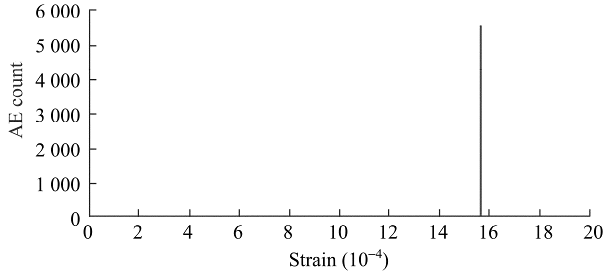
(a) m = 1.5



(b) m = 2.0



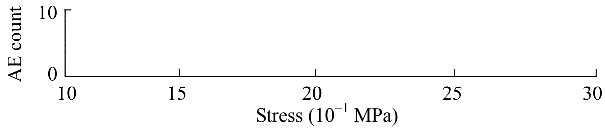
(c) m = 3.0



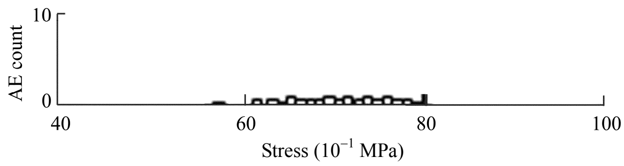
(d) m = 5.0

Fig.2 Effects of rock heterogeneity on precursory laws of macro fracture (numerical simulation by RFPA).

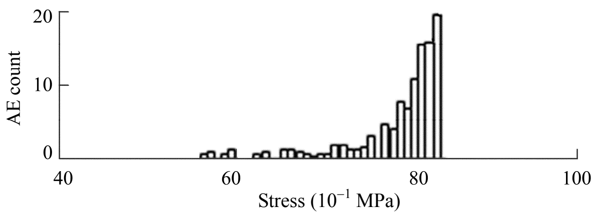
The simulation results are in good agreement with the test results obtained by Mogi (1985). Mogi conducted laboratory tests on rock samples with four different homogeneity indices and the precursory patterns of microcracking are shown in Fig.3. The homogeneity index of colophony is the highest and few precursory microcracking events are detected before rock failure. For the pumice sample that has the lowest homogeneity index, a great number of microcracks are observed before failure.



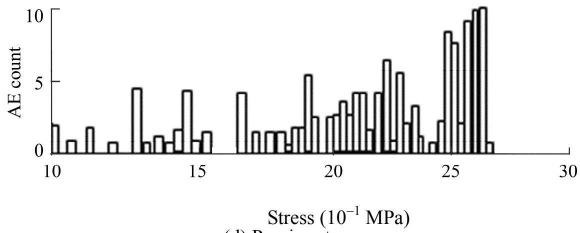
(a) Colophongy.



(b) Trachyte.



(c) Granite.



(d) Pumice stone.

Fig.3 Different precursory patterns of microcracking in rock samples with different heterogeneity indices in laboratory tests. (Mogi, 1985).

In short, the results of both numerical simulation and physical experiment indicate that the precursory microcracking generally occurs before macro failure of rock. This is the basic conception for application of microseismic technique to monitoring and prediction of rockburst.

(2) Deformation localization is the intrinsic cause of rockburst. Studies on rock failure suggest that the failure of rock or rock masses in various scales is localized. For a small-scale rock sample in laboratory test, no matter how it fails (by shear or tension), the sample undergoes the processes from homogeneous deformation to localized deformation until failure. Most rockbursts occur in the tunnel or excavated sections. In a larger scale, the sudden rupture of crust medium (earthquake) usually takes place in the vicinity of plate edges or faults. Appropriate consideration should be given to deformation localization in rock or rock structures in studying rockburst mechanism and prediction.

The deformation localization in rock is mainly caused by two factors. The first is the heterogeneity in geometry or loading. For example, stress concentration around tunnel or crack tips leads to high stress exceeding rock bearing capacity and subsequently local failure happens. The second is the heterogeneity and discontinuity in mechanical properties of the medium. Deformation localization is an important concept in modern mechanics [10, 11], which is closely related to structural instability and failure. Therefore, for analyses of rockburst monitoring data, to capture the information on deformation localization and figure out the development trend may enhance the feasibility of rockburst prediction.

(3) The interaction between rocks and surrounding rocks of excavations is the external cause of rockburst [20]. The interaction is the soul of instability phenomena, leading to high complexity of instability phenomena. For the same rock, when the properties of the surrounding media are different, it may exhibit failure characterized by different sequences and thus different failure patterns. However, further studies indicate that the energy released during rock failure is far more than the energy released by the failure itself. For catastrophic failure like rockburst, the driving source behind rock failure is the release of elastic energy in the medium surrounding the failed rock. Therefore, the traditional rockburst criteria based on stress and strength analyses are not necessarily reliable. Further investigation into the interaction between rock and surrounding environment, particularly the precursory information contained in the unfailed body surrounding the failed body, may bring in new inspiration for monitoring and prediction of rockbursts.

3 Technical feasibility of monitoring and prediction of rockbursts

3.1 Limitations of displacement monitoring

At present, monitoring of displacement or deformation is usually adopted to evaluate stability of large slopes, tunnels and caverns. This monitoring method is suitable for soft rocks or rock masses with relatively large deformation. However, for hard rock or brittle rock structure, no large deformation or displacement can be detected before macro failure. Large deformation or displacement may occur only when the rock structure is in the vicinity of macro failure. Therefore, the traditional displacement or deformation monitoring method can only provide the corresponding large displacement only when the macro fracture has occurred and cannot be used to monitor the evolution process of microcracking (often the precursory microcracking cannot be detected visually) in the rock.

Another limitation of the displacement or deformation monitoring method is that it can only be used to monitor some local points in the rock. The results cannot reflect the deformation or displacement of rock in adjacent region, leading to the difficulties in making the overall stability evaluation of rock structure on a macro scale.

Rockburst is a catastrophic phenomenon triggered by the progressive failure process when hard rock or brittle rock structure is loaded under high stresses. Therefore, the initiation and development of rockburst can hardly be reflected by monitoring deformation or displacement, which limits the application of deformation or displacement monitoring to rockburst prediction.

3.2 Outcome of geostress

From the point of view of mechanism, fracture of any material is inevitably related to high stresses. Therefore, theoretically speaking, as long as one can obtain the stress distributions in the rock structure and the surrounding medium, or find out the location of high stresses, rockburst prediction is possible. However, although many mature monitoring techniques for stresses have been applied to engineering practices worldwide, similar to deformation or displacement monitoring techniques, they are based on measurement of "points" and can only provide the stress state for certain points so far. At present, the information of overall stress field in the engineering structure and the surrounding rocks can not be measured by any single technique. Consequently, rockburst prediction based on stress monitoring is technically infeasible, at present at least.

As we know, excavation of rock structures inevitably leads to stress transfer in the surrounding rocks, in the form of either stress release or stress accumulation. In the region with stress accumulation, microcracking may take place. The microcracking phenomenon reflects the response of rock structure to stresses, namely, the "outcome" of stress field. Therefore, although it is difficult to monitor the stress field in the rock structure, the response of rock structure to stresses (i.e. microcracking) can be monitored. The stress variation laws due to engineering disturbances can be obtained indirectly through analyzing the evolution behavior of microcracking in terms of time, location and intensity.

The microseismic monitoring technique, which is currently under rapid development in the world, can help to achieve this purpose.

3.3 Microseismic monitoring technique

The microseismic monitoring technique is a geophysical method. It can monitor the time and location of microcracks induced during the deformation and failure processes of rock masses. When cracks initiate, propagate and interact in rock, the internally accumulated energy is released in the form of stress waves, which propagate in P- and S-waves and lead to the occurrence of microcracking events. The microseismic monitoring system can transform the received waveforms into electrical signals through geophones or accelerometers and further transform into data signals through the data acquisition system. With the assistant of specialized data processing software, the time, location and magnitude of microcracking events can be determined accurately in real time in three-dimensional space. Accordingly, the range of failed rock, stability and development trend can be evaluated qualitatively or quantitatively. The microseismic monitoring technique can be applied mainly to civil engineering associated with environment and public safety, tunnel excavation, rockburst, slope stability, underground caverns, structural response, dam monitoring; direction of fault activities, stability of oil and gas wells, monitoring and management of oil and gas reservoirs, assessment of hydraulic fracturing, underground oil reserves in petroleum engineering; stability of underground caverns, caving mining, management of goaf area, slope stability of open mines, blasting in mining engineering.

Compared with the traditional displacement or stress monitoring techniques, the microseismic monitoring technique has the following distinctive features:

(1) The monitoring range can be very wide. The time, location and magnitude of microcracking events in rock mass can be determined directly. It overcomes the drawbacks of the traditional "point" monitoring techniques, which are localized, discontinuous, labor-intensive and poor in safety.

(2) It realizes automation, informationization and intelligentization of monitoring, which represents the development trend of stability monitoring for deep underground structures.

(3) The monitoring instruments are being developed towards highly integrated, small-sized, multi-channel and highly sensitive devices.

(4) It supports automatic monitoring and remote information transmission. The monitoring data can be sent to the microseismic data analysis center through wireless GPRS.

(5) As it receives information of seismic waves, the sensors can be installed in the region far away from the failure-prone area, which is advantageous for ensuring long-term operation of monitoring system.

3.4 Feasibility of applying microseismic monitoring technique to rockburst prediction

As mentioned above, rock is heterogeneous, therefore, many microcracks usually form before the macro failure of any rock mass. Microcracking leads to the formation of elastic waves as elastic energy is released. The elastic waves can be captured by microseismic sensors within their effective ranges. A group of sensors can be installed to receive the information of elastic waves. The time, location and magnitude of microcracking in rock mass can then be back calculated. According to the size, clustering and density of microcracks, the development trend of macro fracture can be deduced, in particular the distribution and clustering regularities (i.e. deformation localization) of microcracks. It is then possible to predict the occurrence of rockbursts.

The deformation monitoring technique is suitable for soft rock or soil due to the large deformation and a small amount of energy released upon failure. However, rockburst is generally a catastrophic phenomenon triggered by a progressive failure process when brittle rock structures are loaded under high stresses. The deformation is small and a large amount of energy is released upon failure. Therefore, the microseismic monitoring technique is particularly suitable for prediction of rockbursts.

4 Engineering practices of rockburst monitoring and prediction

Commissioned by Jinping Construction Management Authority, Ertan Hydropower Development

Co., Ltd., Dalian Mechsoft Co., Ltd. set up a movable microseismic monitoring system during tunnel construction of Jinping II Hydropower Station for the first time. The microseismic monitoring system can move with the advancing of TBM and monitor the microseismic activities in real time. The feasibility of rockburst prediction was explored based on the analysis of microseismic monitoring data. Currently, the monitoring system has been under normal operation and some preliminary results have been achieved. In this paper, the preliminary application of microseismic monitoring technique to rockburst prediction during TBM tunneling for this large-scale hydropower project is briefly introduced.

4.1 Overview

Jinping II Hydropower Station is located at the junction of three counties, Muli, Yanyuan and Mianning of Liangshan Yi Autonomous Prefecture, Sichuan Province, China. It takes advantage of the natural elevation drop at the Jinping bend of Yalong River, and water is diverted by a sluice dam to headrace tunnels for power generation. Jinping II Hydropower Station is an important cascade hydropower station on the main stream of Yalong River, with an installed capacity of 4 800 MW and a unit capacity of 600 MW [36].

The Jinping mountain distributes in the Jinping bend approximately in the southwest direction, with multiple peaks and deep valleys, and the maximum elevation drop is over 3 000 m. Jinping II Hydropower Station consists of 7 parallel tunnels. Among them, headrace tunnels No.1 and No.3 are constructed by TBM tunneling and their diameter is 12.43 m. The drainage tunnel is also excavated by TBM with a diameter of 7.2 m. The others are excavated by drill-and-blast method. The maximum excavated cross-section of headrace tunnels No.2 and No.4 is 13 m in diameter and horseshoe-shaped.

Since tunnel construction was commenced, hundreds of rockbursts with various intensities occurred. Among them, the recent two rockbursts were strong and very strong, respectively [37–41].

In 2009, Dalian Mechsoft Co., Ltd. applied the ESG microseismic monitoring technique to tunnel construction of Jinping II Hydropower Station. Data were collected continuously by the microseismic data acquisition system and transmitted to the Mechsoft server in Dalian where they were processed and analyzed. Together with the assistance of a visualization software MMS-View developed by Dalian Mechsoft Co., Ltd., 24-hour continuous monitoring and analysis of microseismic activities during tunnel excavation were realized. Continuous acquisition and collective analysis of seismic monitoring data were achieved, which provided an important platform for studies of rockburst monitoring and prediction during TBM tunneling.

The microseismic monitoring system is shown in Figs.4 and 5. The detailed design and implementation

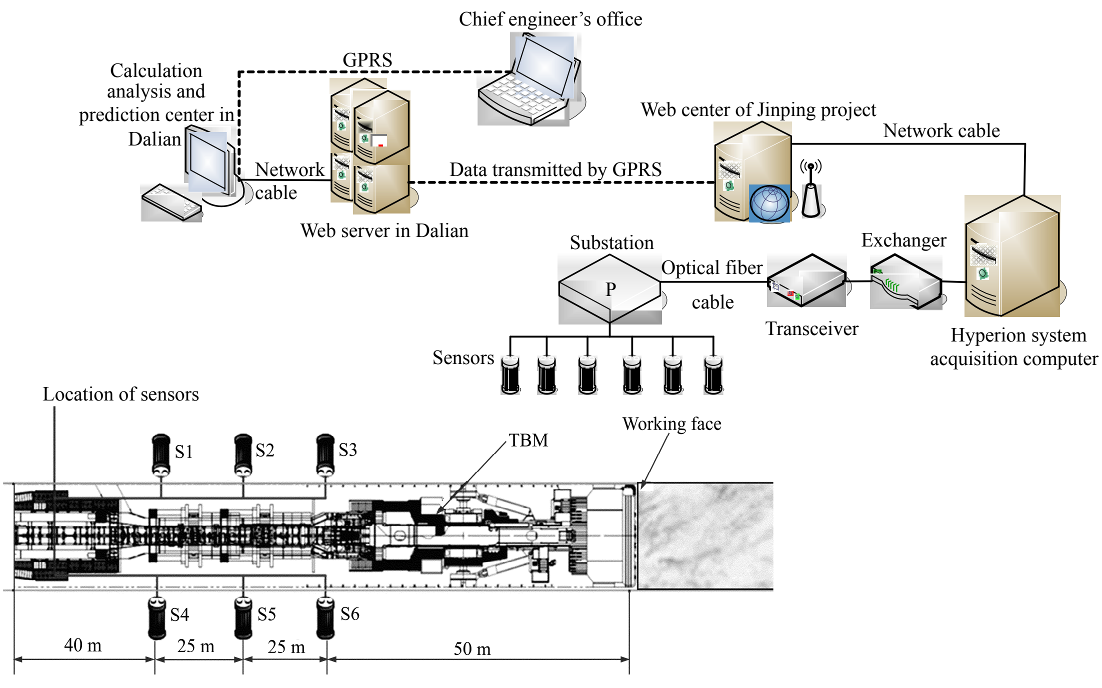


Fig.4 The monitoring and analysis system for rockbursts during TBM tunneling for Jinping II Hydropower Station.

(a)

(b)

Fig.5 The host and substation of the microseismic monitoring system for tunnel excavation.

plan can be referred to the technical report by Dalian Mechsoft Co., Ltd. [15].

4.2 Preliminary results

Figure 6 shows the cumulative distribution of microseismic events within 30 days before a strong rockburst in a tunnel of Jinping II Hydropower Station, where the area of concentrated microseismic events is the center of the rockburst. Figure 7 shows the nephograms of microseismic events within 30 days before the strong rockburst.

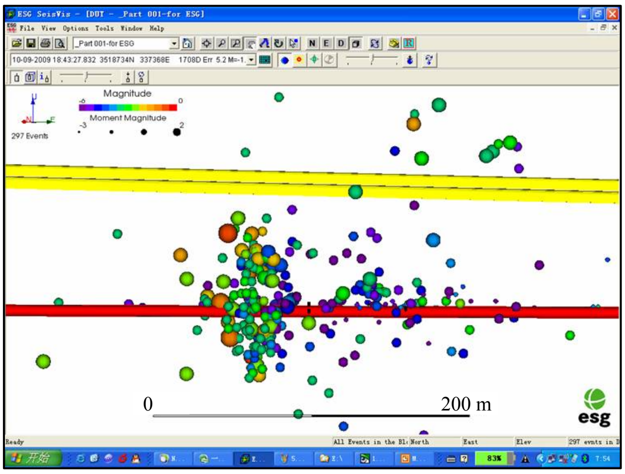
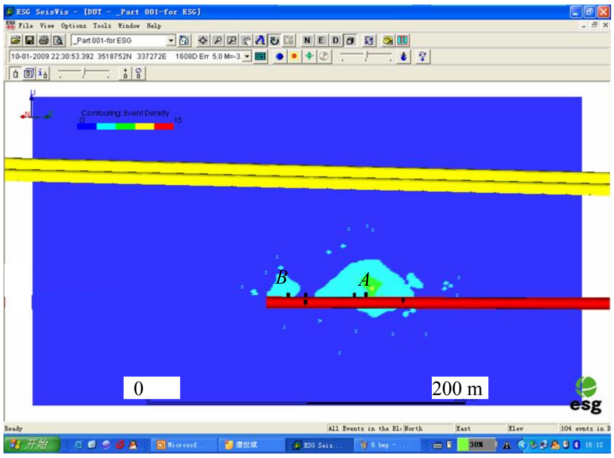
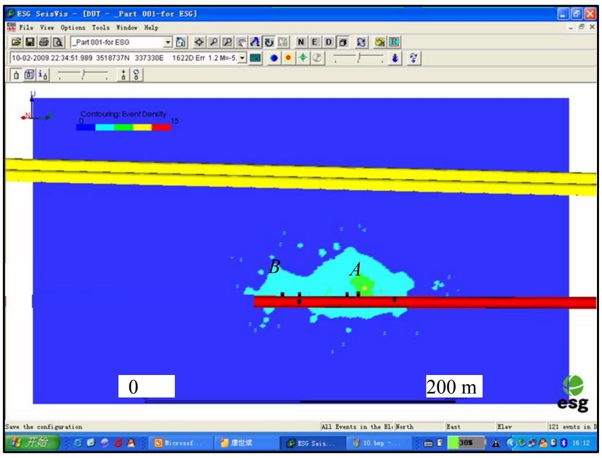


Fig.6 The cumulative microseismic events within 30 days before a very strong rockburst.

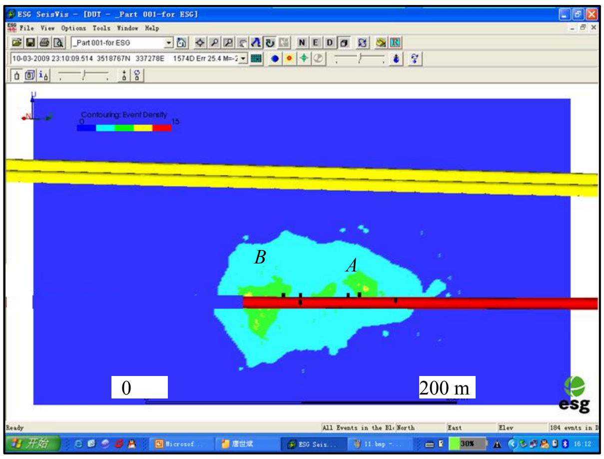
The rockburst took place in the tunnel section below point *B* in Fig.7. It can be seen that the density nephogram of microseismic events appeared near the point *B*, 8 days before the rockburst. With the advancing of tunnel excavation, a rockburst core was formed at the point *B*, 5 days prior to the rockburst. The rockburst occurred 5 days thereafter right at this location. Figure 7 indicates that the location of rockburst has been accurately predicted by the microseismic monitoring system a few days prior to the rockburst.



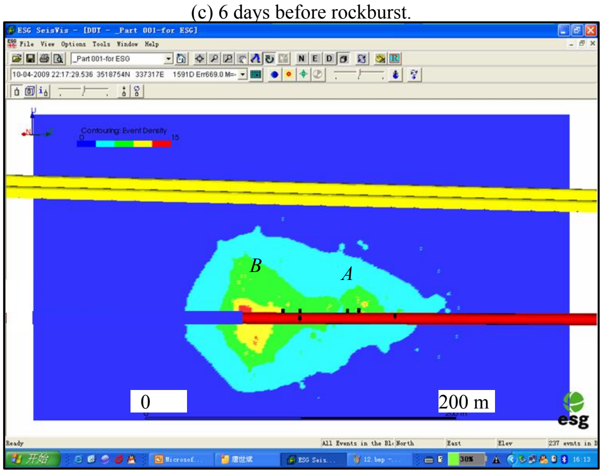
(a) 8 days before rockburst.



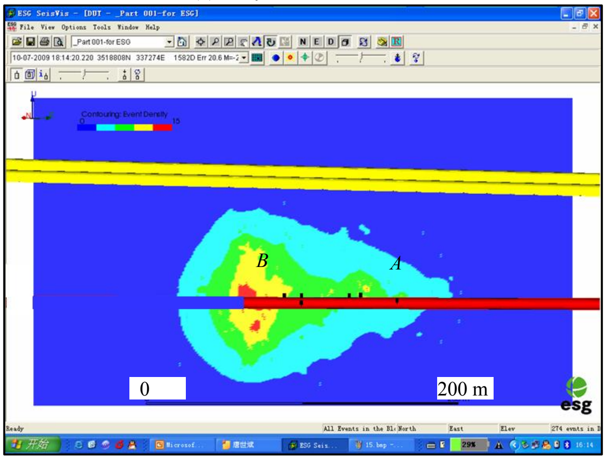
(b) 7 days before rockburst.



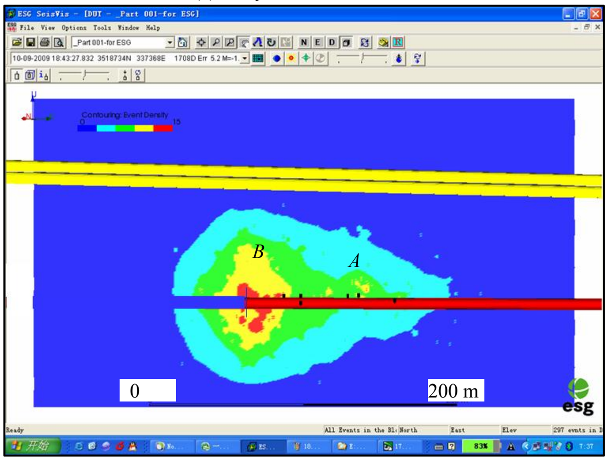
(c) 6 days before rockburst.



(d) 5 days before rockburst.



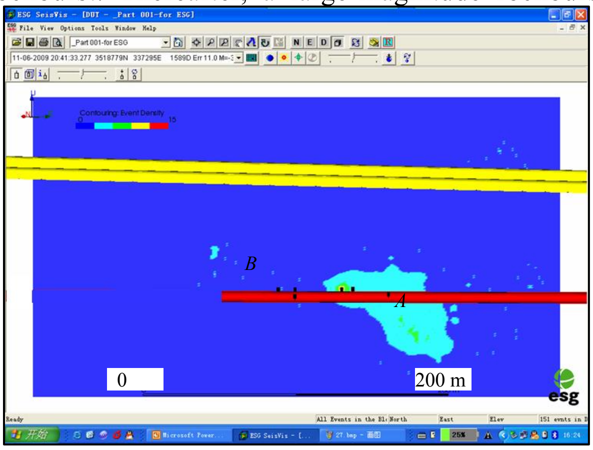
(e) 2 days before rockburst.



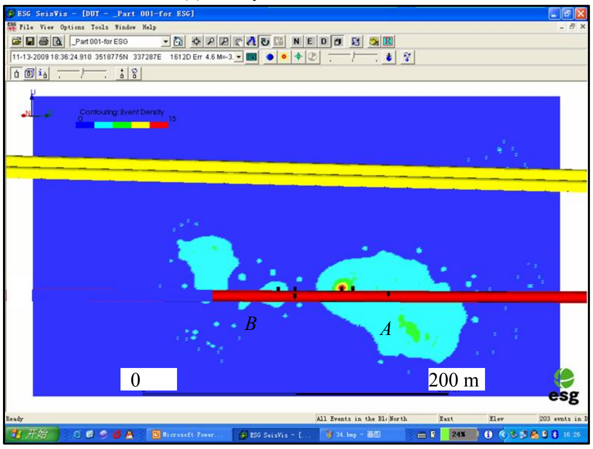
(f) The day of rockburst.

Fig.7 Variations of density nephograms of microseismic events before a rockburst (rockburst occurred in the tunnel section below point *B*).

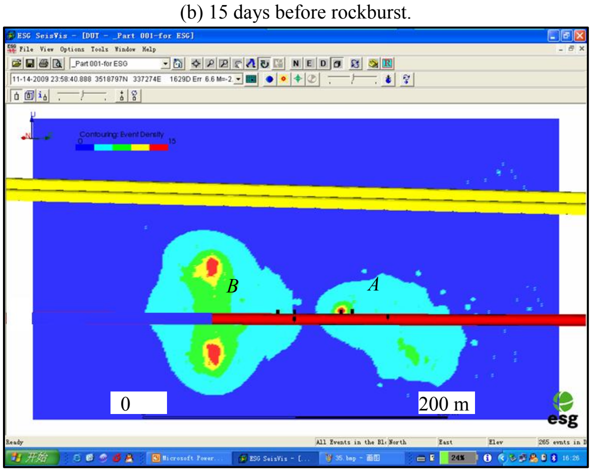
Figure 8 shows the density nephograms of micro-seismic events for another very strong rockburst that occurred less than two months after the previous one. Point *B* was the location of rockburst. The precursors were even more obvious for this rockburst. Anomaly was observed in the nephogram near the point *B*, 14 days before the rockburst. The nephogram core was even more evident at the point *B*, 2 days before the rockburst. Thereafter, a large-magnitude rockburst



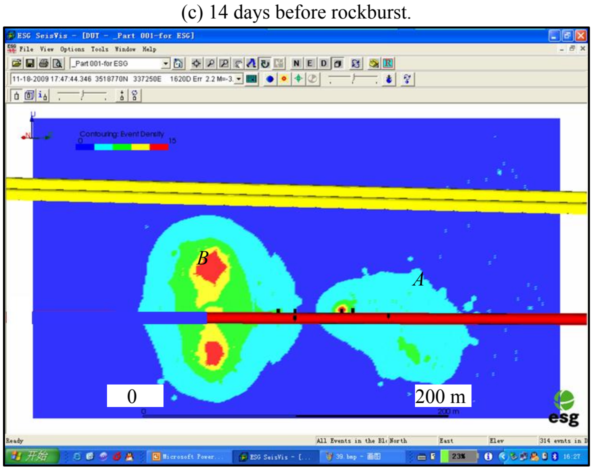
(a) 22 days before rockburst.



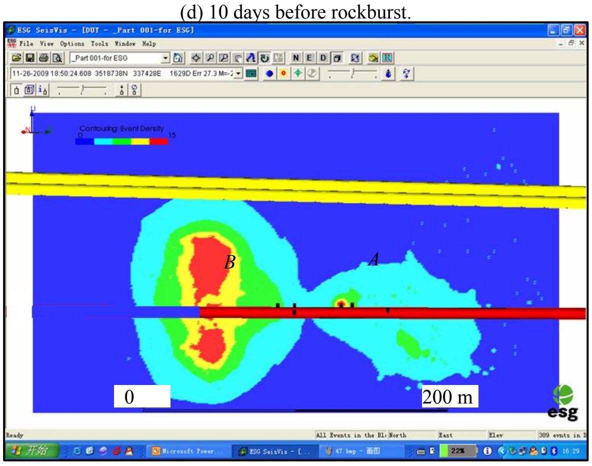
(b) 15 days before rockburst.



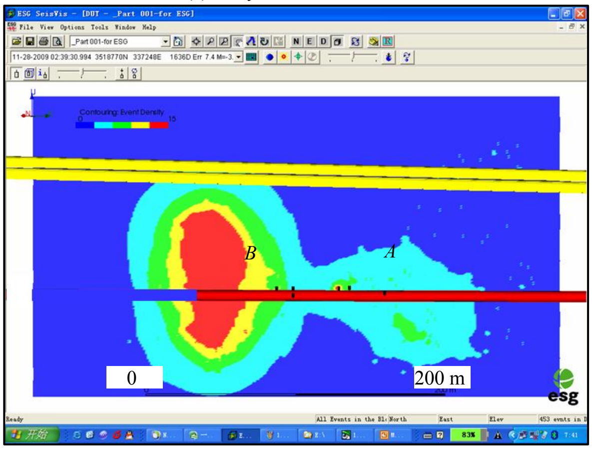
(c) 14 days before rockburst.



(d) 10 days before rockburst.



(e) 2 days before rockburst.



(f) The day of rockburst.

Fig.8 Variations of density nephograms of microseismic events before another rockburst (rockburst occurred in the tunnel section below point *B*).

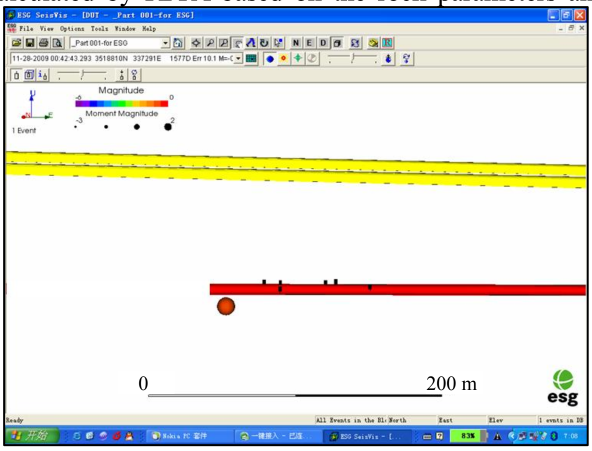
occurred, which resulted in extensive tunnel collapse.

Field inspection indicated that the crater formed by the very strong rockburst was 9 m deep and showed clear signs of structural planes. However, the microseismic location records during the rockburst process shown in Fig.9 suggested that the formation process lasted for 2 minutes, given the crater was as deep as 9 m. Within the 2 minutes from the first microseismic event recorded at 00:42:43 to 00:44:42, about 40 microseismic events were recorded by the microseismic monitoring system. Moreover, most of the microseismic events were distributed along a strip, which tallied with the strike of the structural plane identified during field inspection.

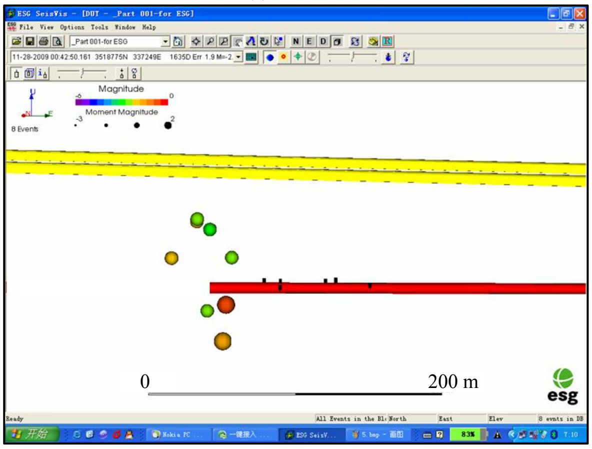
4.3 Discussions

4.3.1 *Effects of structural planes*

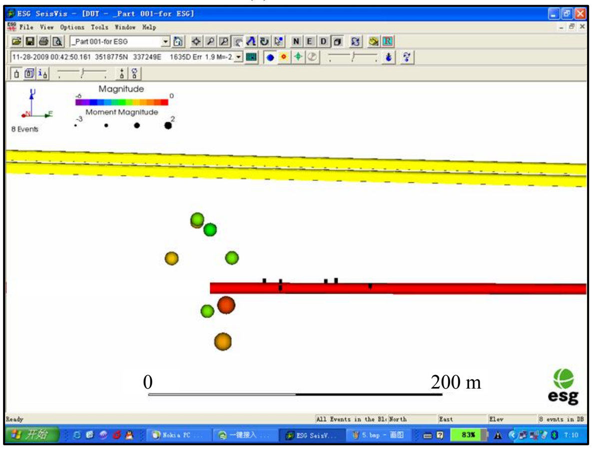
For rockburst monitoring and prediction, special attention shall be paid to the effects of structural planes, weak interfaces and other heterogeneous features in rock masses. Figure 10 shows the distribution of two-dimensional stress field for a tunnel cross-section calculated by RFPA based on the rock parameters and



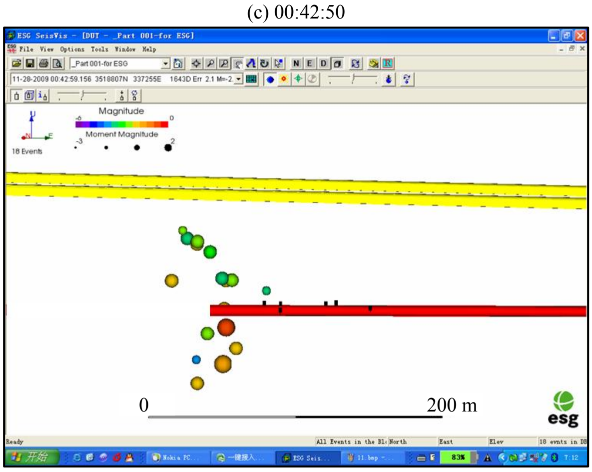
(a) 00:42:43



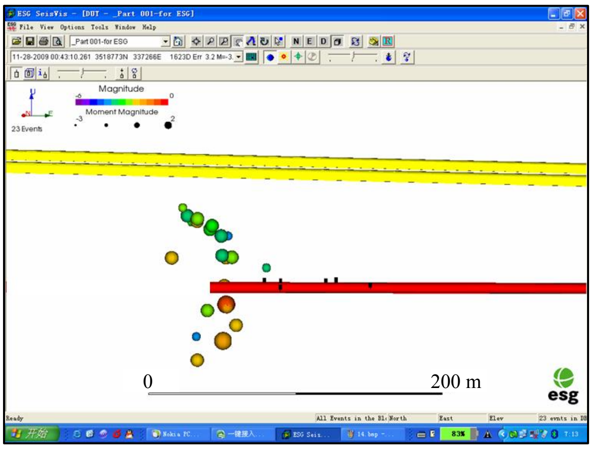
(b) 00:42:48



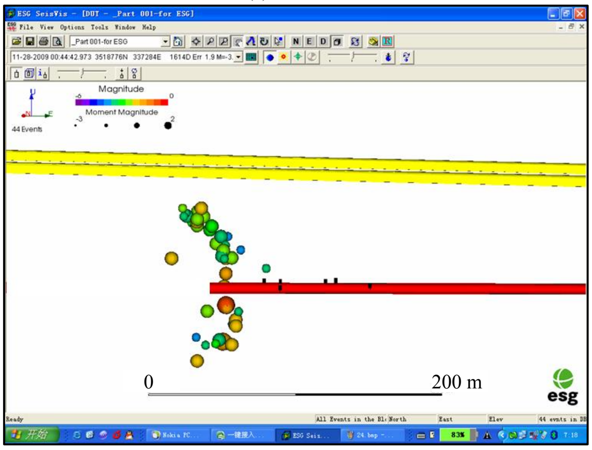
(c) 00:42:50



(d) 00:42:59



(e) 00:43:10



(f) 00:44:42

Fig.9 Microseismic location records during formation of rockburst crater (the formation of rockburst crater lasted for 2 minutes).

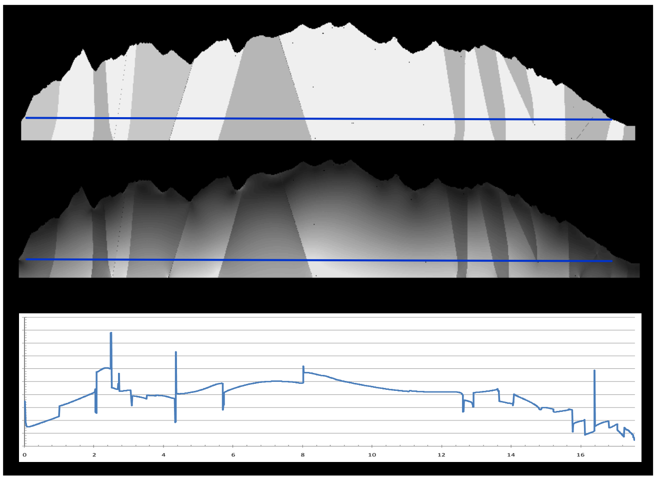


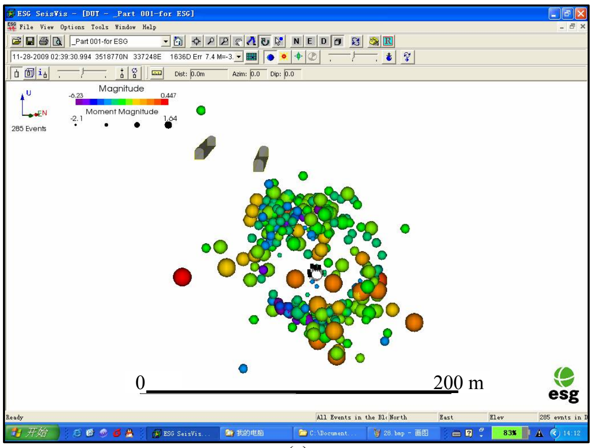
Fig.10 The distribution of relative stress field for a tunnel cross-section calculated by RFPA.

settings of faults, structural planes and weak interfaces provided by the technical data of Jinping II Hydropower Station. In Fig.10, the grey scale in the upper figure stands for the relative elastic modulus, the figure in the middle shows the distribution of the maximum shear stresses with brightness denoting the relative stress, and the curve in the lower figure plots the ratio of calculated principal stress to uniaxial compressive strength.

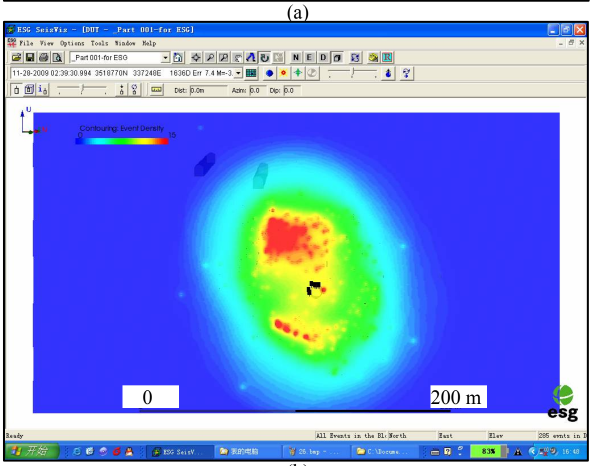
Figure 10 indicates that stress concentration is evident on the structural planes and weak interfaces along the tunnel. It is clearly illustrated in Fig.10 that there is a step rise in the stress field when the rock becomes harder. This region is obviously the location where rockbursts are most likely to occur. The locations of structural planes such as faults are also the dangerous zones for sudden stress change.

4.3.2 *Accuracy of microseismic monitoring data*

Microseismic events can be located with high accuracy along the tunnel axis. However, along the direction perpendicular to the tunnel axis, location may be inaccurate. Figure 11 shows the cross-section of the tunnel that has experienced a very strong rockburst shown in Figs.8 and 9. Most microseismic events took place around the tunnel and formed an approximately closed circle surrounding the tunnel. However, the error in locating microseismic events on the cross-section was quite large as most microseismic events were located far away from the tunnel perimeter.



(a)



(b)

Fig.11 Distribution and nephogram of microseismic events on a tunnel cross-section.

The reason for high locating accuracy along the tunnel axis and low accuracy along the cross-section is that the sensors can only be installed one-dimensionally along the tunnel axis. Therefore, the microseismic events are positioned by the tangent positioning method rather than the intersection positioning method. The tangent positioning method can only assure the location accuracy along the tunnel axis. Nevertheless, one-dimensional location accuracy along the tunnel axis is able to meet the requirement of tunnel construction.

4.3.3 *Problems to be overcome*

(1) Determination of wave velocity. For a tunnel excavated by drill-and-blast method, the wave velocity can be corrected by using blasting data. However, for a tunnel excavated by TBM, the wave velocity in rock can not be determined by precision blasting. In addition, with the advancing of TBM, the rock's properties and structures keep changing and the wave velocity has to be estimated continuously. The microseismic location can hardly be achieved with a high accuracy. Therefore, the wave velocity needs to be corrected iteratively by some known microseismic points with larger magnitudes so that the location accuracy can be ensured.

(2) Determination of the location of seismic source. As the tangent positioning method is currently adopted, the location accuracy can be guaranteed along the tunnel axis, but it is poor in the direction perpendicular to the tunnel axis. It is suggested to monitor the microseismic events from a separate tunnel or hole in the future so that the intersection positioning method can be employed and the location accuracy can be improved.

(3) During the operation time, the advance rate and the time to move grippers are not fixed, and the disturbance on rock masses can not be determined. Therefore, it is difficult to accurately predict the exact time of rockburst, which requires persistent exploration, summary and accumulation.

(4) Constrained by the site conditions, 24-hour continuous monitoring and data analysis cannot be realized in the early stage of monitoring. At present, the microseismic events have been basically monitored and analyzed in real time through optical fiber transmission. However, the optical fibers were sometimes damaged during tunnel construction, which led to an interruption of data transmission.

(5) At present, difficulties are encountered for determining the energy and magnitude of rockbursts. Further exploration and summation of experiences are required.

5 Conclusions and recommendations

(1) The microseismic monitoring results during tunnel construction of Jinping II Hydropower Station indicate that precursory microcracking exists prior to most rockbursts, which can be captured by the microseismic monitoring system.

(2) In terms of distance, some failure precursors can be detected by the microseismic sensors for rockbursts, tens of meters (or more than 100 m) away. The approximate range of strong rockburst can be located by the microseismic monitoring system.

(3) In terms of time, some precursors usually appear a few days before a rockburst event. As the occurrence of rockburst is related to the excavation progress, the exact time of rockburst can hardly be predicted although the location of rockburst may be determined in advance.

(4) In terms of magnitude, at present, only the relative magnitude can be obtained by using analogy according to the site experiences.

(5) The sophisticated RFPA simulation showed that stress concentration was evident near structural planes (such as faults or joints), which should be the focus of rockburst monitoring. The self-weight (γh) can only serve as a reference for rockburst prediction rather than the criterion for rockburst. It is shown that, by integrating the microseismic monitoring and the sophisticated RFPA simulation, the feasibility of rockburst prediction is expected to be enhanced.

(6) The monitoring results indicated that the formation process of some rockburst craters lasted for 2 minutes. This shows that the damaged region is not formed instantaneously. Instead, it is a progressive process. This means that installation of a flexible support system can help to absorb partial energy released by rockburst and delay or hinder further damage of surrounding rocks to a certain extent, so as to mitigate rockburst hazards.

(7) Rockburst prediction based on the microseismic monitoring system needs further exploration. For the headrace tunnel to be constructed by TBM, it is suggested to be monitored through the drill-and-blast tunnel. In this way, the intersection positioning method can be employed to improve the low accuracy due to the current tangent positioning method and to enhance the monitoring accuracy.

(8) Monitoring in adjacent tunnels can not only

improve the monitoring accuracy, but also better ensure the safety of monitoring personnel.

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