Comprehensive monitoring for rockburst at a pumped storage power station in northeast China

Chunhua Zhou1,2, Jianmin Yin1, Yun'an Li1, Zhihong Dong1, Chao Zhou1

1.Key Laboratory of Geotechnical Mechanics and Engineering of the Ministry of Water Resources, Changjiang River Scientific Research Institute, Wuhan, Hubei 430010, PR China; 2.Faculty of Engineering, China University of Geosciences, Wuhan, Hubei 430074, PR China

Abstract. Rockburst is characterised by the wide occurrence areas and the long delayed time at a pumped storage power station in Heilongjiang province of China. For the study, a new method is proposed to identify the induced rockburst based on the combination of microseismic (MS) and electromagnetic radiation (EMR) monitoring methods. EMR monitoring method is introduced to make up for the shortcomings of the monitoring blind area caused by the propagation path of wave velocity during MS monitoring and a beneficial attempt is carried out for the comprehensive application of the two methods to monitor the rockburst. Firstly, a MS monitoring system is established around the underground powerhouse to recognize the propagation of micro-fracture during the deep excavation, while the typical five parameters including the frequency of the microseismic events, the total energy of daily events, energy index ($E_I$), cumulative apparent volume (CAV) and microseismic signal $b$-value are analyzed to reveal the temporal and spatial evolution law of microseismic events. Secondly, an EMR monitoring system is also established near the MS events clustering area to study the characteristics of EMR produced from the fractured rock mass. The temporal and spatial variation of the two parameters including electromagnetic radiation intensity and pulse number are also analyzed and the distribution of higher values are compared with the geological structure. Finally, the correlation of electromagnetic signals, microseismic signals and local stress is studied based on theories of geophysics, electromagnetism and rock mechanics, and some credible results are obtained. Here are the following results: (1) The microseismic events are characterized by spatial clustering, and the joint action of the excavation disturbance and the weak structure body of the surrounding rock mass are the main factors for rockburst. The trend of sharp decrease of energy index and sudden increase of cumulative apparent volume generally indicates the occurrence of rockburst or macro-fracture. The magnitude of $b$ value indicates that the rockburst failure type in the project belongs to fracture-slip rockburst. (2) The sudden change of electromagnetic radiation intensity in the fault fracture zone of the underground powerhouse can be used as the precursor information of rockburst or large-scale rupture events.(3) The micro-fracture activities revealed by EMR and MS methods are consistent in spatial distribution. The distribution of the peak values of electromagnetic radiation pulse number are basically consistent with the direction of the apparent stress migration disturbed by the field construction situation. So we can infer that it will play an important role to improve the accuracy of rockburst prediction based on the analysis of the multi-source signals.
1. Introduction

As one of the most complex dynamic disasters, rockburst is well known not only it is uncertain to reveal accurately when and where rockburst happen but also its mechanical mechanism is still not uniform[1]. The situation is related to many factors affecting rockburst, such as ground stress, geological structure and the disturbance of excavation. At present, many researchers and engineers have successfully obtained a deep understanding of the influence of various factors on rockburst through different methods such as theory, numerical simulation, indoor experiment and in-site monitoring, but they still can not accurately predict when and where rockburst will occur, and the relevant research is still at the stage of hypothesis and experience[2-7].

Among the above research methods, in-situ monitoring is the most direct and effective method to study rockburst. Especially, microseismic monitoring technology is widely applied for monitoring and early warning of rockburst in different fields based on the analysis of the source characteristics of the seismic waves induced by the excavation disturbance and the micro-fracture activities. From the beginning to the middle of the 20th century, Germany and the United States monitored the rockburst about mining with the application of microseismic monitoring technology earlier. P. K. Kasier and S. M. Maione[8] have studied the relationship between the failure mechanism of rockburst and microseismic events. S. J. Gibowicz[9] studied the mechanism of rockburst induced by mining activities by using microseismic monitoring technology, and verified the possibility of early warning by this technology. The microseismic monitoring instruments was developed firstly in 1950s in China and applied to monitor the rockburst in Mentougou Mine[10]. Later, with application of microseismic monitoring systems from Poland, South Africa, Canada and other foreign countries, the monitoring and early warning practice of rockburst were carried out and some progress was made[11,12]. Engineering practice shows that the method is not only rich in data, but also clear in physical meaning of source parameters, which can provide a strong basis for the analysis of rockburst or micro-fracture activity in the field. For example, Chinese scholars F. Dai, B. H. Zhang, N. W. Xu, etc[13-15], have studied the deformation, failure mechanism and stability of surrounding rock of underground powerhouse of Baihetan, Dagangshan, Houziyan hydropower stations based on microseismic monitoring technology or some conventional monitoring methods, which has accumulated successful experience for the application of this monitoring technology in disaster prediction during underground cavern excavation. However, in these successful cases, the monitoring method is relatively simple, and the wave velocity is generally constant in the positioning calculation theory of microseismic monitoring system. This inevitably leads to the fact that MS method is difficult to apply to the monitoring of fracture or rockburst induced by the excavation of large underground caverns in hydropower stations or many large stopes in mines. In order to solve the above problems, the electromagnetic radiation method is proposed for local dynamic continuous monitoring to make up for the deficiency of MS method. As a non-contact dynamic monitoring method, electromagnetic radiation method has been experienced successfully in many cases for the monitoring and early warning of rockburst in deep coal mines or metal mines[16-22]. Engineering practice shows that microseismic monitoring method is characerised by the fixed-point and passive monitoring, while electromagnetic radiation monitoring method is characerised by the mobile and active monitoring, which forms a beneficial supplement in monitoring mode and monitoring range. In theory, it can comprehensively identify the precursor information of the activity of the micro-fracture or induced rockburst, and deepen the understanding of the preparation process of rockburst.

In view of the complexity of rockburst induced by deep excavation of underground powerhouse at a pumped storage power station in northeast China, microseismic and electromagnetic radiation monitoring system were firstly introduced in the field of hydropower and water conservancy project. The monitoring results realized the identification of different precursor information during the preparation of rockburst and revealed the characteristics of microseismicity and electromagnetic radiation activity. Combined with actual geological conditions, the internal relationship between electromagnetic radiation, microseismic and local stress field was further analyzed. The
comprehensive monitoring results based on the two methods are consistent with the engineering practice, which provides a reliable basis for monitoring and early warning of rockburst, and is of great significance to engineering safety construction.

2. Background of the project

2.1. The features of engineering and geological background

Huanggou Pumped Storage Power Station is located in the northeast of China and installed capacity of 1.2 million kW (4 sets of 300,000 kW units). The underground powerhouse of the power station is arranged in the middle of the water conveyance tunnel, with a vertical buried depth of 310 m and a horizontal buried depth of about 1200 m. The long axis of the cavern is in N49°W, and the excavation size is 150.5 m × 24.0 m × 53.4 m (length × width × height). The project is located in a small structural basin. The lithology of strata mainly includes metamorphic rock and volcanic rock, and the bedrock of the underground powerhouse is granite of Variscan period. The regional tectonic is mainly composed of NS Mudanjiang faults, accompanied by NNE faults, approximately EW, NE and NW faults (shown in figure 1). There are four steep faults in the underground powerhouse, including the reverse fault f31 with strike EW and dip S (upstream), the translating fault f32 with strike N15°W and dip NE, the translating fault f33 with strike N21°W ~ N30°W and dip NE, the translating fault f34 with strike N55°W ~ N67°W and dip SW. According to the in-situ stress test results, the strength-to-stress ratio of surrounding rock mass is between 4 ~ 7 and the magnitude of stress is at intermediate level. The results also show the direction of maximum principal stress is nearly horizontally in EW and the stress field is mainly controlled by tectonic stress.

Figure 1  Sketch map showing the regional structures and the distribution of the typical rockburst of Huanggou pumped storage station

2.2. Characteristics of rockburst

A few slight rockburst happened widely in almost all of the underground caverns and resulted in 5 cm ~ 20 cm thick spalling during the early construction of underground caverns by drilling and blasting method in 2015. Especially from 2016 to 2017, the moderate rockburst occasionally occurred. According to the statistics, the main characteristics of some typical slight and moderate rockburst in site are shown in and figure 1 and table 1. The intensity of rockburst is characterised with mainly slight, while moderate especially in the intersection of caverns or near the fault structures. The failure signs of rockburst vary with different intensity (figure 1) and it can be summarized that the slight rockburst resulted in bursting loose and flaking, while moderate rockburst resulted in collapsing with blasting pit in 1 m depth.

Based on the characteristics of surrounding rock mass structures, the buried depth and the cavern trend of typical rockburst in table 1, it can be inferred that rockburst is greatly influenced by the density of...
joints and mainly happens in more than 300 m in vertical buried depth, while the cavity axis' orientation slightly affects rockburst. The typical rockburst occurred at the intersection of 3# construction adit and the right end wall of the underground powerhouse is just in the stress concentration area. So it can be preliminarily judged that the stress concentration caused by the excavation disturbance and the weak structural body of surrounding rock mass are the comprehensive causes for the induced strain-structural plane slip rockburst.

| Date       | Location          | Rockburst failure                                      | Characteristics of the surrounding rock | Depth and trend of the caverns |
|------------|-------------------|--------------------------------------------------------|----------------------------------------|--------------------------------|
| 20160101   | NO.2 construction adit | Slight rockburst of left top arch and arch shoulder     | Two groups of steep joints developed in the left roof arch and side wall, while the joint plane is closed | 380 m/N41°E                  |
| 20160409   | NO.3 construction adit | Moderate rockburst in the top arch resulted landslide  | Two NW-NWW faults developed nearby, with hard and intact rock | 380 m/N49°W                  |
| 20160528   | NO.3 construction adit | Slight rockburst near the top arch and arch shoulder with flaking | Rock mass is hard and relatively intact with joints slightly developed | 385 m/N49°W                  |
| 20160625   | Middle rainfall gallery | Local slight rockburst                                 | Common joints of surrounding rock mass | 336 m/N49°W                  |
| 20160807   | NO.3 construction adit | Slight rockburst near the top arch and arch shoulder with flaking Moderate rockburst near the top arch resulted in a small-scale landslide | The rock is hard and the joints are slightly developed | 410 m/N49°W                  |
| 20170827   | NO.3 construction adit | Intersection of two faults                             | Joints are slightly developed and rock mass is relatively intact | 370 m/N49°W                  |
| 20170919   | NO.4 construction adit | Slight rockburst near the top arch with flaking after two years’ excavation |                                         | 170 m/N49°W                  |

3. Comprehensive methods for monitoring the rockburst

3.1. Principles of the monitoring methods

Rock mass deforms and fractures with the deep excavation in the underground powerhouse. Deformation and fracturing are mainly induced by the propagation of micro-fractures which released the energy in sound wave forms. The MS system records and analyses the activity of micro-fractures (called as MS events) in real-time. Based on the method, the exact time and location, especially the intensity of MS events can be detected in many vibration parameters (energy, frequency, source radius, moment magnitude, and stress). The MS monitoring system is widely in use for the real-time, three-dimensional, dynamic, remote monitoring style. Based on some theories, the MS monitoring system can be used to analyze the distribution of local stress field.

Through the rock mechanical experiments, it can be found that the EMR phenomenon accords with the deformation and fracturing. Generally the relationship between EMR energy and stress is based on the assumption that the rock mass is composed of micrograins, while the micrograins, the micrograins’ strength and failure separately obey the Hooke’s law, Mises yield criterion and the Weibull distribution.
Assuming the theoretical analysis, the relationship between the EMR intensity and stress is in nonlinear positive correlation. When the stress increases at the maximum value, the EMR intensity reaches the maximum level. In other words, the EMR intensity reflects the stress level in rock mass and so EMR can be used to monitor and predict rockburst. Therefore, the EMR method is suggested to be applied in the early stage of the rockburst monitoring.

3.2. MS monitoring method and equipment
Canada ESG high-precision microseismic monitoring system is applied for the rockburst monitoring in site, and the monitoring is carried out according to the corresponding monitoring technical requirements. The MS monitoring system is shown as figure 2 and there are 18 uniaxial accelerometer sensors arranged inside the upper and middle drainage corridor. To achieve the purpose of monitoring the micro-fracture activity of surrounding rock mass between the underground powerhouse and surrounding drainage corridors, the space formed by existing underground caverns such as drainage corridors are made full use of, ensuring that underground caverns such as underground powerhouse are located in the sensor space array. The final monitoring scope covers the main caverns such as underground powerhouse, main transformer room and tailgate room (figure 3). In order to minimize the source wave velocity error caused by the heterogeneity of rock mass and ensure the positioning accuracy of the monitoring system, the system is calibrated by manual percussion test and wave velocity determination. By evenly selecting 17 different P wave velocities in the range of 4700 ms\(^{-1}\) ~ 5500 ms\(^{-1}\), and calculating the corresponding positioning errors of 10 percussion experiments, the optimal wave velocity of surrounding rock in the monitoring area is finally determined to be 5150 ms\(^{-1}\)\([23]\).

Figure 2 Schematic diagram of stratified excavation of underground powerhouse and sensor position
3.3. EMR monitoring method and equipment

In the same way, combined with the characteristics of the rockburst, the portable EMR equipment (YDD16) is used as the monitoring equipment. The electromagnetic radiation intensity, pulse number and the frequency bandwidth ranges from 0 mV to 500 mV, 0 Hz to 5000 Hz and 500 Hz to 500 kHz, respectively. Non-contact directional monitoring is adopted in the monitoring process and the measuring point is arranged every 10 m along the rock wall. The antenna is fixed at a distance of 1.5 m above the ground and vertically apart from the rock wall in 0.2 m. The effective monitoring range is approximately 7 m~22 m in distance and the maximum radiating angle reaches up to 60°. In the process of acquisition, the data acquisition time of each monitoring point is 2 minutes. Based on the experience of EMR monitoring in mine and the space condition in site, the drainage corridors around the underground powerhouse and the main transformer room, the tailgate room and the tailbranch are all monitored in the research. Firstly, the background EMR signal of the surrounding environment is monitored. Secondly, the surrounding corridors at different elevations including the upper, middle and down drainage corridors are separately monitored. Finally, the potential rockburst range of the middle drainage corridor in construction is specially monitored continuously. Due to the limitation of the contents, the monitoring results of the middle drainage corridor will be introduced with emphasis next (Figure 4).
4. Results of the comprehensive monitoring methods

4.1. Characteristics of the microseismic events

For the deep recognition of the propagation of micro-fracture during the excavation, the typical five parameters including the frequency of the microseismic events, the total energy of daily events, energy index, cumulative apparent volume and microseismic signal b-value are all analyzed separately.

4.1.1. Temporal and spatial distribution of the induced microseismic events. In order to minimize the error about the source wave velocity caused by the heterogeneity of the rock mass and ensure the positioning accuracy of the monitoring system, the system is calibrated by manual percussion tests and wave velocity determination methods and the optimal velocity is 5150 ms⁻¹ [23]. Through 4 months' real-time monitoring, 692 effective events were detected in underground powerhouse area, including 481 microseismic events and 211 blasting events. The spatial distribution of microseismic events is shown in figure 5, showing three clustering zones, namely, clustering zone ①-the arch shoulder of left section form K0+0 m ~ K0+70 m in the main powerhouse upstream side, clustering zone ②-3# construction adit near the side wall of the powerhouse installation room, and clustering zone ③-the rock stratum of the layer III near the upstream side wall in the powerhouse to be excavated. Combined with the spatial distribution of the early rockburst, it can be found that the distribution of the microseismic events in different clustering zones is consistent with the rockburst in the corresponding areas with the deep excavation of the powerhouse, which indicates that the surrounding rock stress is still in the process of constant adjustment resulting in frequent micro-fracture activities.
4.1.2. Relationship between the frequency and energy of the microseismic events. According to the microseismic information process by the microseismic monitoring system, the relationship between daily accumulated released energy $E_d$ and the microseismic event frequency $N$ can be analyzed, as shown in Figure 6. It can be inferred from the figure that the distribution of frequency and energy of microseismic events in the monitoring range can be roughly divided into two stages. There is the stage I showing that the frequency is higher, while the energy is lower and low-energy microseismic events are more frequent. There is another stage II showing that the frequency of microseismic events is relatively low, while rockburst or high-energy microseismic events occur immediately after the sharp increase of energy. Usually, at the initial stage of rockburst (stage I), the micro-cracks in surrounding rock mass are in the process of initiation and development under the action of external disturbance, which is mainly manifested by the high frequency and low-energy microseismic events. At stage I, the rockburst will occur and a large amount of energy is suddenly released when the micro-fracture expands rapidly and penetrates the surrounding or primary micro-fracture in a large area, indicating that the actual monitoring results are consistent with the general law of rock burst preparation.

4.1.3. Characteristics of the energy index and the cumulative apparent volume. In seismology and statistics theory, the apparent volume and energy index are all important physical quantities used to describe the process of earthquake preparation and development. These parameters reflect the evolution law and change characteristics of surrounding rock mass rupture before earthquake. The existing research and engineering experience show that rockburst usually occurs when the cumulative apparent volume increases rapidly and the energy index drops rapidly. Therefore, the precursory information of micro-fracture before rockburst can be obtained through the variation characteristics of parameters such as energy index and apparent volume.
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With the intensive construction activities such as blasting, the number of microseismic events increase gradually while the logarithm of energy index ($\log(EI)$) decreases of (shown in figure 7(a) stage I, II and III and figure 7(b) stage I and II) and the cumulative apparent volume (CAV) increases gradually. It reveals that the change of energy index and cumulative apparent volume is more obvious in figure 7(a) showing a maximum increase of 1000 $m^3$ about the cumulative apparent volume and a maximum decreases of 2.0 about the logarithm of energy index in December. According to the physical meaning of the cumulative apparent volume and the energy index, it can be inferred that the release of energy from the surrounding rock mass in December is relatively large. After the compaction and elastic stages, the rock mass is in the strain softening and rock burst incubation stage, corresponding to the decline process of the energy index logarithm in figure 7(a) stage I, II, III and figure 7(b) stage I, II. It indicates that there is the possibility of inducing rockburst when the energy index shows a sharp drop. The corresponding phenomena are shown in figure 7, such as the surrounding rock mass broke while accompanied by a cracking sound on 25 December 2017 in figure 7(a) and the surrounding rock mass collapsed on 17 January 2018 in figure 7(b). By comparing the failure of surrounding rock mass in site and the monitoring results, the trend shown in figure 7 is consistent with the phenomenon of rockburst happened in the field. Therefore, it can be considered
that the induced precursors of rockburst can be effectively identified by analyzing the evolution law of cumulative apparent volume and energy index of microseismic events.

4.1.4. Variation of the b-value. Through the statistical study of earthquake magnitude and frequency related to seismic activity in the world, the magnitude-frequency (G-R) relationship is suggested by B. Gutenberg and C.F. Richter[24]. A large number of experiments and engineering practices show that the microseismic events induced by the excavation disturbance, including natural earthquake events, obey the law. The formula can be expressed as follows.

\[ \log N(M) = a - bM \]  

(1)

Where \( M \) is the magnitude, \( N(M) \) is the total number of microseismic events with magnitude greater than \( M \), and \( a \) and \( b \) are constant during a monitoring period. For different types of microseismic events, the value of \( b \) is directly related to the focal mechanism. According to the researchers’ results[24,25], \( b \) is less than 0.8 for the fault-slip seismicity, while the value ranges from 1.2 to 1.5 for the stress-migration seismicity induced by mining and blasting in generally. At the same time, some studies have shown that \( b \) reflects the proportional relationship between the number of slight earthquakes and the moderate or intense earthquakes in a certain area. When the \( b \)-value increases, it shows that there are more slight earthquake events, less moderate or intense earthquake events and the surrounding rock mass is relatively stable. When the \( b \)-value decreases, it indicates that slight earthquake events decrease, while moderate or intense earthquake events begin to increase, and the stability of rock mass gradually decreases. Combined with the engineering practice, when the dynamic disaster did not occur, the \( b \)-value gradually increased due to the increase of slight microseismic event. The \( b \)-value tends to be stable when the engineering rock mass is in quasi-equilibrium state (quiet period), while the value drops sharply when the rock mass suddenly suffers dynamic disasters, showing the increase of moderate or intense microseismic events and the decrease of slight events.

![Graphs showing variation in b-value](image)

Figure 8 Variation law of \( b \) value during the monitoring period

It can be inferred that the distribution of the \( b \)-value shows three stages of rising at first, then stabilizing and finally plummeting during the continuous 4 months’ monitoring. In fact, there are few micro-fractures in the surrounding rock mass during the early monitoring period, and the slight and
moderate or intense microseismic events happened rarely showing a small \( b \)-value (0.5). Then, with the deep excavation, the microseismic events are mostly small ones, and the \( b \)-value increases at first and then keeps stable (from 0.5 to 0.7 ~ 0.8 shown in figure 8). Finally, a rockburst happened in site under the influence of the continuous disturbance resulted in the sharp decrease of the \( b \)-value from 0.7 to 0.3. Therefore, the change of the \( b \)-value reflects the influence of construction disturbance to a certain extent. Combined with the above mentioned theory and the \( b \)-value, it can be concluded that rockburst induced in the project is mainly fracture-slip type.

4.2. Characteristics of the electromagnetic radiation activity

The temporal and spatial distribution of electromagnetic radiation intensity and pulse number near the fault fissure zone in the upstream side of the underground power house is analyzed in detail. The distribution of electromagnetic radiation intensity is obviously different between the fault fracture zone and the relatively intact surrounding rock mass (figure 9), that is, the electromagnetic radiation intensity of monitoring points 1 # ~ 8 # located in the relatively complete surrounding rock section is obviously higher than that of monitoring points 9 # ~ 15 # in the fault fracture zone. Combined with the excavation situation, the electromagnetic radiation intensity is greatly affected by the construction disturbance and gradually tends to be stable when the construction intensity is weakening. It can be obviously found that the fluctuation range of electromagnetic radiation intensity in the fractured zone is greater than that in the relatively intact zone in figure 9. In detail, the electromagnetic radiation intensity of monitoring points 11 # ~ 13 # suddenly increased from nearly 100 mV to 400 mV at the early stage of construction. After the field survey, crackling sound and roof arch surrounding rock collapse appeared near the cave wall on 22 December 2017 and was proved by the monitoring results. So it was indicated that the sudden increase of electromagnetic radiation intensity provided strong evidence for the delineation of potential rockburst areas.

![Figure 9 Temporal and spatial distribution of electromagnetic radiation intensity](image)

In view of the temporal and spatial distribution of electromagnetic radiation intensity shown in figure 10, the overall distribution shows a M-shaped outline during the monitoring period and the peak value of electromagnetic pulse number shifts from monitoring point 5# to point 3#, with a time span of about 8 days. Accounting for the electromagnetic radiation monitoring method is more widely applied in mining field, the changes of the peak value of electromagnetic radiation pulse number are not so significant in the surrounding rock mass as in the coal media. Due to the time limitation, the variation amplitude of the pulse number in different media will be carried out in the subsequent studies, so as to further study the internal relationship between the pulse number variation and stress migration. Considering the basic theory that electromagnetic pulse number mainly reflects the frequency of
micro-fracture and is directly related to the local stress field, the local stress in the monitoring range migrates from the center of the power house to the right end wall of the power house (i.e., the 5# monitoring point faces the 3# monitoring point), and the adjustment time of in-situ stress is about 8 days, which is completely consistent with the dynamic process of construction. Through the analyses, it can provide a basis for the stress migration direction and adjusting time about the local stress field.

![Temporal and spatial distribution of pulse number](image)

**Figure 10** Temporal and spatial distribution of pulse number

### 4.3. Correlation between MS, EMR, and the local stress

Microseismic monitoring information mainly reveals micro-fracture activities in a large range (about 100 m in space around the sensor, while electromagnetic radiation information obtained by portable fixed-point continuous monitoring method reflects the dynamic distribution of micro-fracture in a local range (7 m ~ 22 m inside the rock wall). Therefore, the micro-fracture activities revealed by the two methods can complement each other in space, and the time of identifying the precursor information of micro-fracture activities by electromagnetic radiation method is slightly earlier than MS method, which is proved in the reference[26].

Generally speaking, the apparent stress inferred from microseismic information often represents the stress release level, and there is a positive correlation between the both parameters including electromagnetic radiation intensity and pulse number and the loading intensity and the frequency of rupture activity, respectively[22, 26]. For the accurate load intensity is difficult to be obtained, the external load intensity can be indirectly reflected by the construction intensity. The higher the electromagnetic radiation intensity, the higher the electromagnetic radiation intensity. It is proved by the law of electromagnetic radiation intensity caused by construction activities such as blasting and excavation for 3 consecutive days in figure 9. The the changing trend between the normalized number of microseismic eventsand the pulse number is basically consistent in figure 11, indicating that the pulse number of electromagnetic radiation pulse is also positively correlated with micro-fracture activities. Therefore, the correlation among MS, EMR intensity (or pulse number) and local stress field can be established by analyzing the changing trend of apparent stress based on the real-time monitoring information. By drawing the apparent stress nephogram (figure 12), it reveals that the apparent stress in surrounding rock mass has gone through two stages. During the first 14 days, the interior of the surrounding rock mass is in a high value adjustment period and the maximum apparent stress is 42.393 kPa. Then in the third week, the maximum value of apparent stress plummets from 42.393 kPa to 21.830 kPa and the scope of the source area continues to extend towards the installation room of the main power house, indicating that the stress migration direction is on the side of the installation room of the main power house. In the last week, the apparent stress of surrounding rock mass continues to decrease to 18.633 kPa, and the scope of the source area increases slightly. At the
same time, the distribution of higher pulse number in the previous stage corresponds to a higher level of apparent stress. The peak value of pulse number in the later stage decreased obviously, corresponding to the lower level of apparent stress. In addition, the peak value of pulse number shifts from monitoring point 5# to monitoring point 3#, which is completely consistent with the migration direction of apparent stress mentioned above. So it can be concluded that there is a good correlation between the apparent stress, electromagnetic radiation pulse number and the local stress, which can provide scientific guidance for the safety of construction.

Figure 11 Trend of the normalized electromagnetic radiation pulse number and microseismic events number

(a) 2017.12.19～2017.12.25  
(b) 2017.12.19～2017.12.31  
(c) 2017.12.19～2018.1.7  
(d) 2017.12.19～2018.1.12

5. Conclusions
Through the comprehensive monitoring of micro-fracture activities with the deep excavation of Huanggou pumped storage power station by MS and EMR methods, the following conclusions can be drawn:

(1) The microseismic events are characterized by spatial clustering, and the joint action of external construction disturbance and geological weak structure are the main factors for rockburst. The trend of rapid decrease of energy index and large increase of cumulative apparent volume indicates the occurrence of rockburst or macro-fracture. The magnitude of $b$-value indicates that the rockburst failure type in the project is fracture-slip rockburst.

(2) The sudden change of electromagnetic radiation intensity in the fault fracture zone of underground powerhouse can be used as the precursor information of rockburst or large-scale rupture events. The peak distribution trend of electromagnetic radiation pulse number indicates the adjustment direction of local stress field caused by construction disturbance.

(3) The micro-fracture activities revealed by EMR and MS methods are consistent in spatial distribution. The peak distribution of electromagnetic radiation pulse number is basically consistent with the apparent stress migration rule, and is consistent with the field construction situation. There is a good correlation between the three kinds of information, which is beneficial to reveal the adjustment trend of local stress field in the source area. Therefore, the comprehensive monitoring method of MS and EMR will play an important role to improve rockburst prediction accuracy.

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