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EMR: An effective method for monitoring and warning of rock burst hazard

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Abstract. Rock burst may cause serious casualties and property losses, and how to conduct effective monitoring and warning is the key to avoid this disaster. In this paper, we reviewed both the rock burst mechanism and the principle of using electromagnetic radiation (EMR) from coal rock to monitor and forewarn rock burst, and systematically studied EMR monitored data of 4 rock bursts of Qianqiu Coal Mine, Yima Coal Group, Co. Ltd. Results show that (1) Before rock burst occurrence, there is a breeding process for stress accumulation and energy concentration inside the coal rock mass subject to external stresses, which causes it to crack, emitting a large amount of EMR; when the EMR level reaches a certain intensity, which reveals that deformation and fracture inside the coal rock mass have become serious, rock burst may occur anytime and it's necessary to implement an early warning. (2) Monitored EMR indicators such as its intensity and pulses amount are well and positively correlated before rock bursts occurs, generally showing a rising trend for more than 5 continuous days either slowly or dramatically, and the disaster bursts generally occurs at the lower level within 48 h after reaching its peak intensity. (3) The rank of EMR signals sensitive to rock burst in a descending order is maximum EMR intensity > rate of change in EMR intensity > maximum amount of EMR pulses > rate of change in the amount of EMR pulses.

Keywords: coal rock mass; rock burst; electromagnetic radiation; monitor and forewarn

1. Introduction

Coal is China's main energy with its proportions of 76.9% and 69.3% in the primary energy production and consumption structure, respectively (State Administration of Work Safety 2014). Rapid development in economics and society forces China's demand for coal to stay at very high level. With near exhaustion of shallow coal resources in eastern China in recent years, many mines have begun mine deep coal resources at a speed of 100~250 m/(10a) (Jiang *et al*. 2009). According to statistical data from China's State Coal Mine Safety Supervision Bureau (State Administration of Coal Mine Safety 2014), the mining depths of more than 300 mines in 43 coal mining regions including Yanzhou, Pingdingshan, Huainan, and Fengfeng are deeper than 600 m. Among them,

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the mining depths of nearly 200 mines in Kailuan, Beipiao, Xinwen, Shenyang, Changguan, Jixi, Fushun, Fuxin, Xuzhou, etc are deeper than 800 m; the mining depths of 47 mines including 21 mines in Shandong Province are deeper than 1000 m. At present, the Suncun Mine in Xinwen mining area is the deepest mine with mining depth over 1500 m. In addition, Huaneng Hetaoyu mine located at Huating, Gansu Province, is characteristic of incline excavation and has main incline shaft length and vertical depth of 5875 m and 975 m, respectively.

With the mining depth increasing and the mining intensity enhancing, the geological structures of some mining areas become more and more complex, leading to rapid increase in rock burst disasters. At present, China has a total of 142 rock burst mines located respectively in 20 provinces, municipalities and autonomous regions, including Shandong, Heilongjiang, Liaoning, Hunan, Sichuan, Henan, and others, as shown in Fig. 1.

Rock burst can inflict not only great damage to roadways, supports and equipments, but also heavy casualties on underground workers and staff. In recent years, almost every year occurred many rock bursts that caused casualties. According to incomplete statistics, the 2010.10.8 rock burst disaster of Kuangou Coal Mine, Xinjiang caused 4 deaths; the 2012.03.31 rock burst of Liangbaoshi Coal Mine, Feicheng, killed 2 miners; the 2013.1.12 rock burst disaster of Wulong Coal Mine, Fuxin, took 8 lives.

Due to its great harmfulness, the research on rock burst is of self-evident significance. As a typical coal or rock dynamic disasters, its burst has a complex evolutionary process of breed, development, and outburst. How to accurately monitor and effectively forewarn it through the changes in physical or mechanical properties of coal rock before its outburst is the key to prevent and control it. To this end, in this work, we, based on the review of both the rock burst mechanism

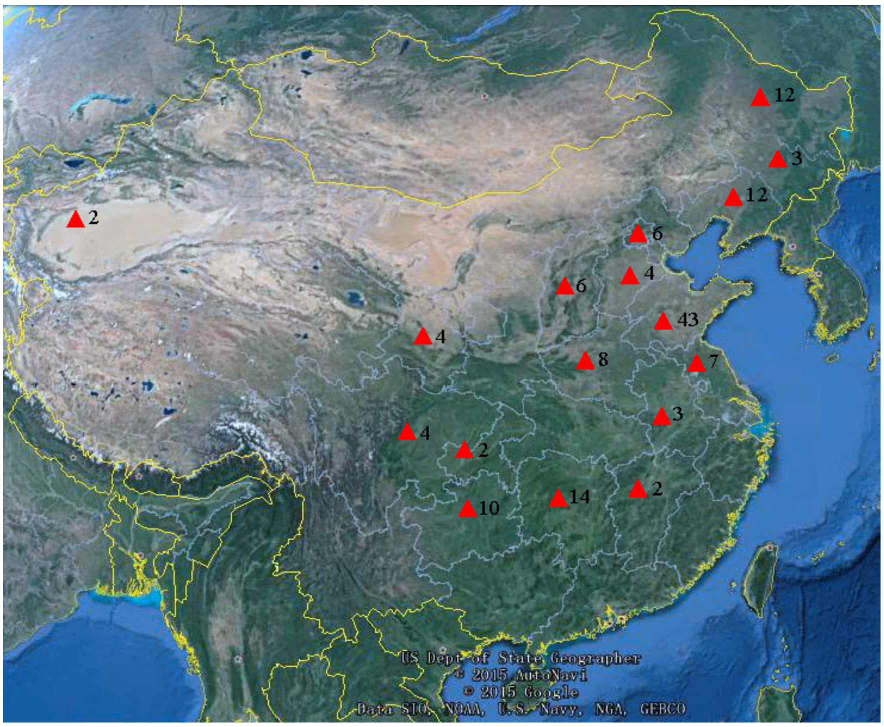


Fig. 1 Distribution and amount of rock burst mines in China

and the principle of using electromagnetic radiation (EMR) from coal rock to monitor and forewarn rock burst, systematically analyzed EMR monitored data of 4 rock burst accidents of Qianqiu Coal Mine, Yima Coal Group, Co. Ltd., and studied the sensitive indicators and prewarning methods using EMR signals from coal rock to monitor rock bursts. The research results are of practical significance for the prevention and control of coal mine rock bursts.

2. Mechanisms of rock bursts

The current systematical studies on the mechanisms of rock bursts based on laboratory experiments and field investigations include three major contents (Jiang *et al*. 2009): (1) exploring the characteristics of coal-rock burst failure and its internal inducing factors from the physical and mechanical behaviors of coal rock materials' point of view, and analyzing the process of coal-rock burst by applying a variety of nonlinear theories; (2) analyzing the relationship of coal-rock bursts to geologic weak planes and coal-rock geometric structures based on the geologic structure of rock burst locations and deformation localization; and (3) investigating the effects of various in-mine power disturbances on rock bursts from the engineering disturbance and mining-induced actions' point of view.

In earlier studies, researchers put forward a series of rock burst models and theories from different angles including strength theory (Brauner 1994, Ortlepp and Stacey 1994), rigidity theory (Cook 1965a, b), energy theory (Cook *et al*. 1965), bursting liability theory (Bieniawski 1967 and Bieniawski *et al*. 1969), "three criteria" theory (Li *et al*. 1984, Li 1985), and instability theory (Zhang 1987, Zhang *et al*. 1991).

In recent years, with the development and application of mathematics, mechanics and other interdisciplinary studies in rock bursts, the use of fracture mechanics, damage mechanics, as well as fractal theory, bifurcation, chaos, and other nonlinear theories opens up new paths for studying rock burst mechanisms.

Vesela (1996) and Beck and Brady (2002) respectively proposed centralized energy storage element, burst sensitive factor and other concepts. Lippmann (1987) and Lippmann and Cheng (1989) presented a coalbed burst "elementary theory" with the structural instability as its starting point, and established a rock burst model with consideration of the relative slip between coal bed and roof or floor. Xu *et al*. (1995) independently applied the catastrophe theory to explain the instability of stope coal (rock) pillars and found the criteria for coal (rock) pillar instability. Wang and Park (2001), Pan *et al*. (2008) and Liu (2013) adopted the catastrophe theory to analyze faults-induced rock bursts and raised the critical conditions of burst instability of the coal/rock system and the expression of related energy-released amount. Xie *et al*. (1993) introduced the fractal geometry and damage mechanics into their research on the mechanism of rock bursts on the basis of microseismic events distribution, and believed that: (1) rock burst is in fact equivalent to a fractal cluster of fractures within rock mass; (2) the dissipation of its energy exponentially increases with the fractal dimension decreasing; and (3) when the fractal dimensions falls to its minimum, its energy dissipates most dramatically, leading to occurrence of rock burst. Pan *et al*. (1998) applied the theory of fractal geometry to study the characteristics of changes in fractures of coal mass after earthquakes, and based on which, proposed a method using coal vibration method to control rock bursts.

Qi *et al*. (1997), based on the creep and rheological behaviors of loaded coal and rock masses, analyzed the friction slip characters and stability of coal rock, and applied the viscous sliding instability mechanism for well explaining the rock burst phenomena, and based on which proposed "three factors criteria" for coal rock structural failure. Xu and Xu (1996) proposed a simple mechanical model for coal pillar rock burst under the viscoelastic roof, and used the cusp catastrophe theory to discuss the mechanism of unsteady rock bursts. Zhou and Xian (1999) experimentally and systematically studied the characteristics of viscoelastic creep in coal rock, proposed the use of the viscoelastic creep compliance coefficient of coal as the criterion for coal creep instability, and established the grading standard for coal burst proneness strength. Miao *et al*. (1999) established a time-dependent diacritical crack extension equation for sub-critical extension of surrounding rock cracks subject to high stress and introduced the time parameter into the rock burst criterion. Zhang *et al*. (1999) analyzed the time bifurcation characteristics of the plate-beam stability, proposed that rheological behaviors of rock mass are closely related to the plate girder instability, and further investigated the mechanism of delayed rock bursts in deep mines. Dou and He (2001) established an elasto-visco-brittle catastrophe model for coal and rock burst failure and based on which, analyzed the characteristics of brittle failure and the time effect of coal material under stress, and better explained the mechanism of rock bursts.

Although all the theories mentioned above discussed the mechanism of rock burst from different angles, they all focused on the stress accumulation and release of coal rock masses as well as energy accumulation, dissipation and release in coal masses. In fact, rock burst itself is a dynamic phenomenon due to instantaneous, sudden outburst of elastic deformation energy accumulated for a longer term in the coal rock mass. Thus, before outburst, there must be a long-term process of stress accumulation or energy concentration under external environmental actions. Correspondingly, this process must be accompanied with coal and rock structural damages under external stress, which makes it possible for us to study the methods of monitoring and early warning rock bursts from the angles of coal rock deformation and failure, as well as fracture evolution.

3. Principle of using electromagnetic radiation (EMR) to detect rock bursts

Coal rock due to its internal deformation and fracture emits EMR. A variety of relevant researches as numerical modelings (Rabinovitch *et al*. 2007, Caboussata and Miers 2010, He *et al*. 2012, Kachakhidze *et al*. 2015), laboratory investigations (Rabinovitch *et al*. 2001, Koktavy *et al*. 2004, Mastrogiannis *et al*. 2015), and field measurements (Nardi and Caputo 2009, Ramulu *et al*. 2009, Hachay *et al*. 2014) have proven that coal rock in its deformation and failure process emits EMR. Our study also has shown (Wang *et al*. 2008) that the EMR is resulted from deformation and failure of coal and other heterogeneous materials subject to loading, and generated by migration of charged particles due to non-uniform deformation of different parts of coal and variable motions of charged particles during fracture expansion. Studies have shown (Wang *et al*. 2011a, b, Song *et al*. 2015) that coal rock during the loading-induced deformation process emits EMR with different intensity corresponding to its subjected external loading. With the load increasing, the instability failure in coal rock mass becomes intense, resulting in an increase in EMR signal intensity. The greater the load is, the more intense the intensity of EMR signal, as shown in Fig. 2.

The essence of rock burst phenomenon is the sudden unstable failure of coal rock mass in the high stress state. According to the sudden unstable failure of coal rock due to stress, rock bursts fall into three categories: unstable material type, slip dislocation type, and unstable structure type (Jiang *et al*. 2011).

The unstable material type rock burst refers that when the concentrated stress in the rock masses around roadway or face during coal excavation reaches a certain intensity level, fractures inside coal or rock materials begin to continuously expand, connect, and aggregate, leading to sudden outburst at some scope of coal rock mass and damages of roadway or face at the scene to some degree, as shown in Fig. 3(a).

The slip dislocation type rock burst refers to the dynamic phenomena generated by sudden and high-speed slip dislocation of coal seam due to significant rigidity difference between coal seam and its roof and floor under mining impact. The representatives of this type of rock bursts are the coal seam translation-induced burst model proposed by Lippmann (1987), and those dynamic rock burst phenomena resulted from the slip or dislocation of faults, tectonics, or structural planes in the vicinity of mines and roadways, as shown in Fig. 3(b).

The unstable structure type rock burst is the dynamic outburst phenomenon of rock masses around the roadways or face due to mining stress, sudden breaks of large areas of suspended roof, or mine seismicity. This type of rock burst is frequently seen in large areas of rocks surrounding coal pillars or roadway, resulting in instability of overall roadway structure, as shown in Fig. 3(c).

Thus, the principle of EMR used for monitoring and forecasting rock bursts can be summarized as follows: (1) the stress abnormality causes localized weak support coal rock to crack, leading to

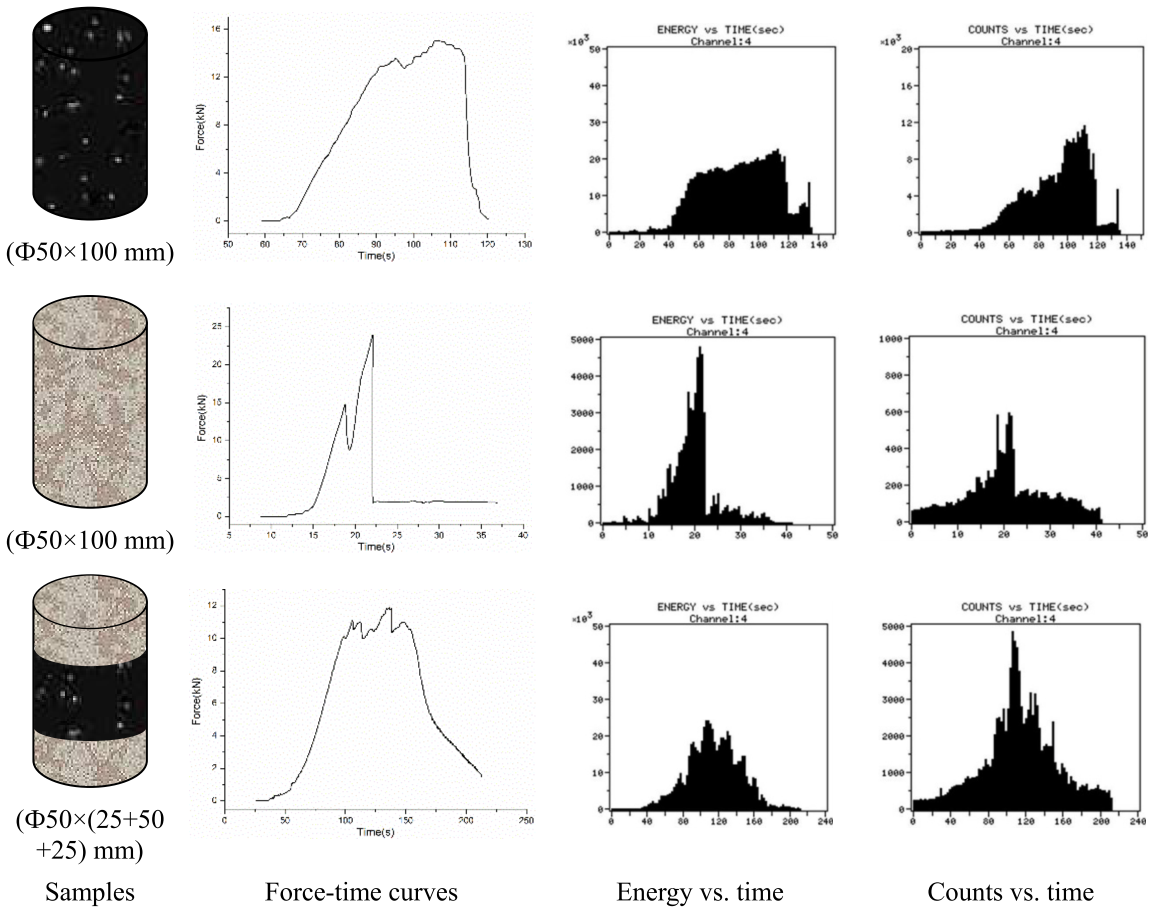
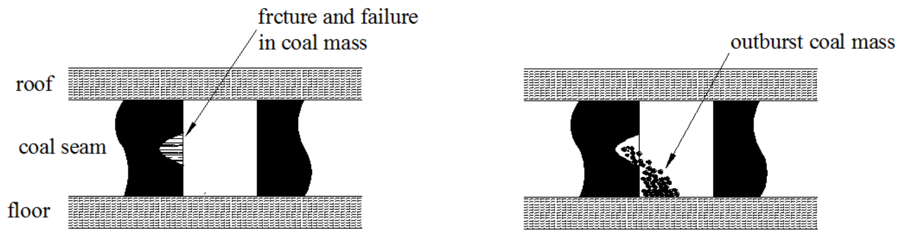
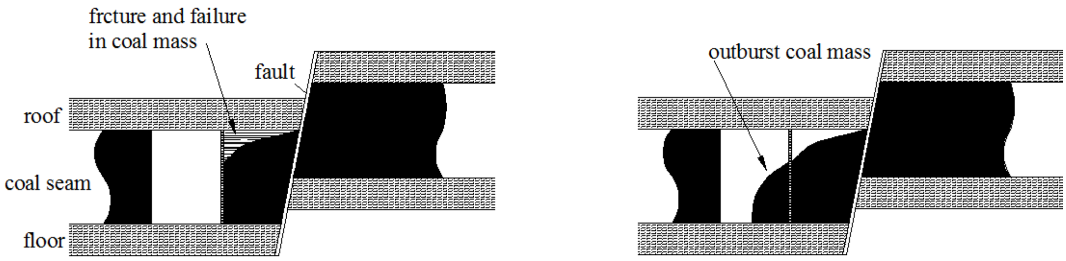


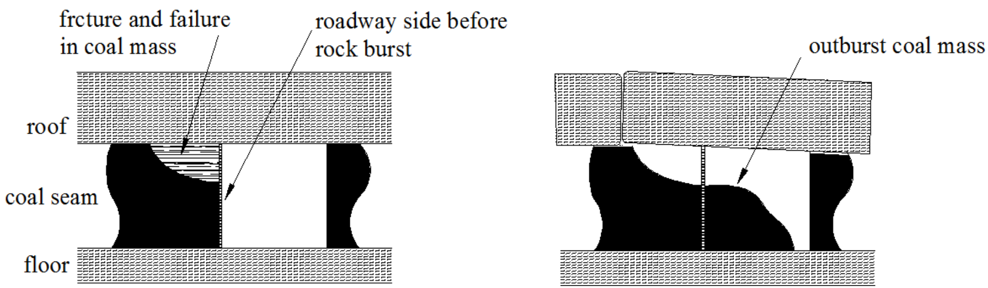
Fig. 2 Load - time curves of coal rock material under uniaxial compresion and characteristics of its relevant EMR sig



(a) Unstable material type



(b) Slip dislocation type



(c) Unstable structure type

Fig. 3 Schematic of coal rock mass deformation and failure before and after the occurrences of different types of rock bursts

4. Field analysis of EMR data

Since 2009, we applied our real-time EMR monitoring and early warning rock burst technology in Qianqiu Coal Mine of Yima Coal Group, Co. Ltd. The mine has been troubled by long-term, very serious rock bursts. In this section, we particularly analyzed the measured EMR data of during the rock burst accident occurring from May to Aug. 4, 2011.

4.1 Impacting factors of Qianqiu Coal Mine rock bursts

The major minable coalbeds of Qianqiu Coal Mine were No. 2-1 and No. 2-3 coalbeds. These two coalbeds under the elevation of +200~250 m were combined into No.2 coalbed with dip of 3°~13° and average thickness of 23.6 m. Most of the mine was minable. The intermediate roof of the coalbed was dense mudstone of 26 m in thickness, the basic roof was fine sandstone of 16 m in thickness, and the overlying stratum above the caprock of the coalbed was the conglomerate bed of up to 240 m in thickness.

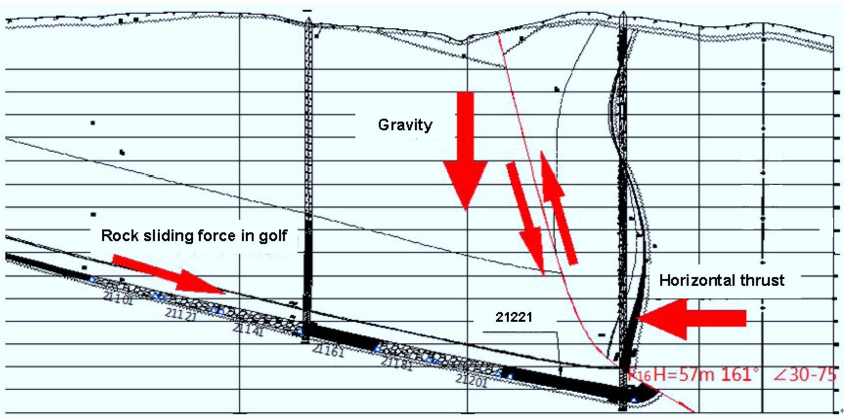


Fig. 4 Major impacting factors of Qianqiu coal mine rock bursts

In recent years, with the mining depth increasing in Qianqiu Coal Mine, rock burst disasters become worse. According to statistics, since 2009, rock bursts or mine seismicities affecting coal production totaled up to 49 times. From Fig. 4, the major factors causing rock bursts are as follows. (1) Yima coal field is characteristic of a synclinal structure. Qianqiu coal mine is located close to the wing section of its synclinal axis. Under the joint action of the large F16 fault, a significant horizontal tectonic stress forms in the coal seam. The measured maximum horizontal stress at No. 21 mining area was 22.87 MPa, 1.17 times as the maximum vertical stress (19.54 MPa). In addition, the tectonic stress increases with the mining depth increasing. (2) The caprock of the coal seam is a thicker conglomerate stratum covered by an about 410 m thick conglomerate stratum, whose activities have great impacts on the development and explosion of rock bursts. (3) The thickness of No. 2 coal seam is about 26 m in average and more than 30 m in maximum, resulting in the presence of additive tectonic stress inside the coal seam. (4) Currently, the mining depth of Qianqiu coal mine is greater than 800 m, far over the average depth (380 m) of coal mines with rock bursts in China. (5) According to the bursting liability obtained using standard testing methods published by the GB/T 2517.1-2010 and GB/T 2517.2-2010 (Standardization Administration of the PR of China 2010), coal seam of Qianqiu coal mine has the weak (classed II) bursting liability.

4.2 Overview of 21141 Face

All data in this paper were collected from No. 21141 Face of Qianqiu coal mine. Fig. 5 shows the location of No. 21141 Face of Qianqiu coal mine. The face has average mining depth of 684.4 m, strike length of 1185 m, dip length of 130 m, and useful coal thickness of 8.8~11.1 m with average of 10.6 m. In addition, the face has no region with sudden thickness change, thus belongs to a relatively stable coalbed with greater thickness.

The immediate roof of the face is dark gray mudstone characteristic of well developed bedding, the thickness of 23.02~27.63 m with an average of 25.44 m, and a more stable distribution. The main roof is the Middle Jurassic Mawa Formation and Upper Jurassic motley glutenite and sandstone with a greater thickness of 410 m in average, the floor from top to bottom is the gangue interbed, carbonaceous mudstone, pebbly mudstone, fine sandstone, siltstone, and conglomerate, with an unstable distribution. The face passes through F3-7 fault and F3-9 fault whose falls are 3 m

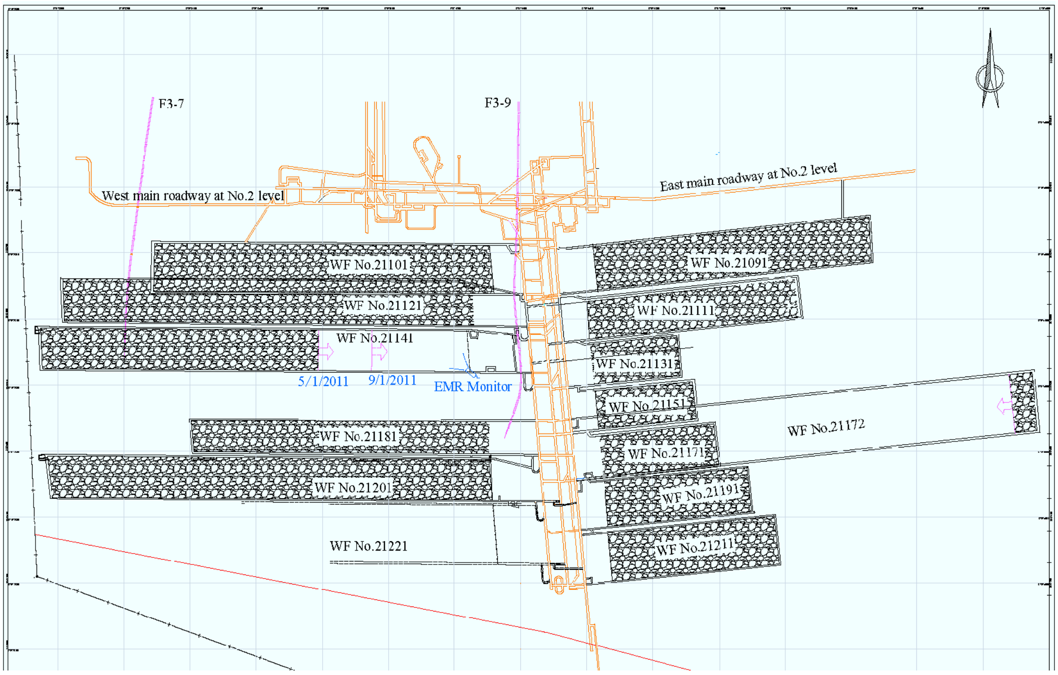


Fig. 5 Location of No. 21141 Face in Qianqiu coal mine

or so. With a simple geological structure, the face was actually excavated through its upper and lower roadways.

4.3 Field monitoring instruments

A mine-used KBD-7 I.S. coal & gas outburst (rock burst) EMR monitoring instrument was used in the field measurement, as shown in Fig. 6. It can be connected with the mine monitoring system and deeply installed or embedded into the stress abnormal zones, the tectonic zones, and

Fig. 6 KBD7 EMR monitor used for measuring the intensity of released stress and the amount of damage pulses

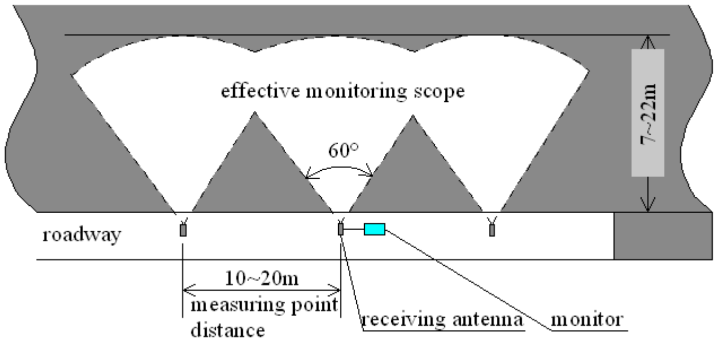


Fig. 7 Schematic of EMR monitor in operation and its effective monitoring scope

the similar potential rock burst areas for real-time and continuous monitoring EMR signals emitted from the coal rock mass subjected to external stresses. It was capable of acquiring two EMR signal indicators, i.e., the signal intensity and the number of pulses. The former could reflect the intensity of stress (energy) released out of coal rock mass during their deformation and failure or fracture, while the latter could detect the frequency of damages occurs inside the coal rock mass

The monitor has the following main technical parameters: (1) ferrite antenna, (2) effective monitoring direction of 60°; (3) effective monitoring range of 7~22 m, as shown in Fig. 7; (4) band width of received signals of 1~400 kHz and dynamic gain of 30 dBu; (5) instrument sensitivity of 1.61 mV/m, 0.67 mV/m and 0.33 mV/m at preamplifier working at 46 dB, 54 dB, and 60 dB, respectively; and (6) instrument sampling frequency of 1~5 MHz.

During the 21141 Face advancing and early pre-mining stages, the stress abnormal zone should be near the stopping line and affected by some small-scale dynamic manifestations. Therefore, the KBD7 was placed in the vicinity of the stopping line of the haulageway of the Face, as shown in Fig. 5. From May 1 to September 1, 2011, the face advanced from 480 m far away from the monitor to about 300 m. According to the literature (Dou and He 2001), because the instrument lay far outside of the stress concentration zone prior to the face, the direct impact of mining at the face could be excluded.

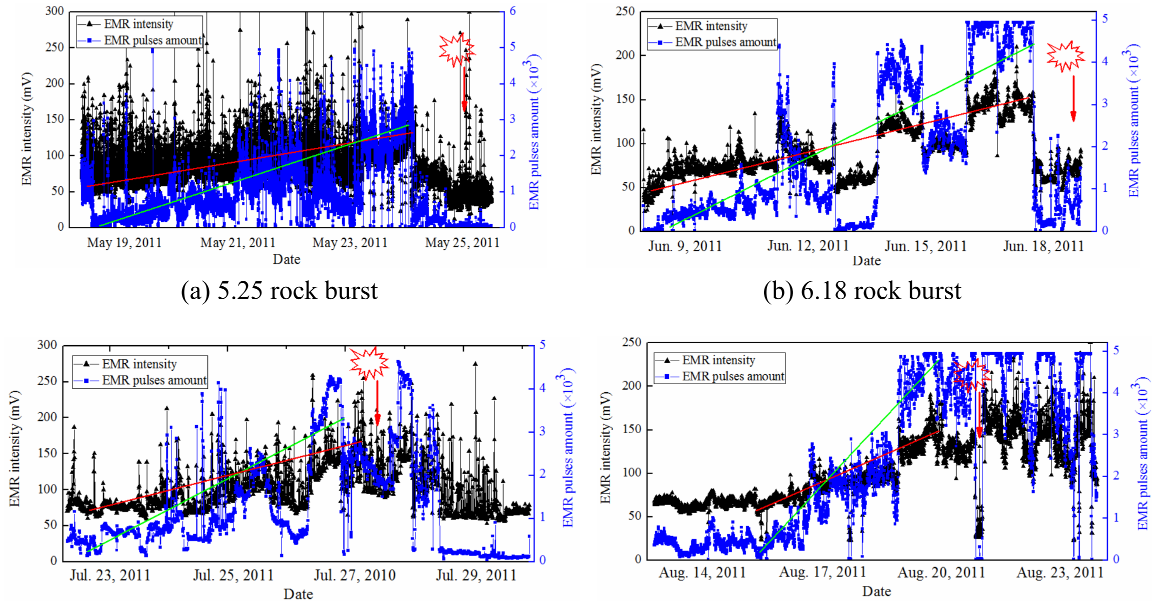
4.4 Analysis of measurement results

4.4.1 Characteristic curve of typical EMR signal precursor and its qualitative analysis

During May to August 2011, rock bursts at the 21141 Face occurred frequently. Among them, four events seriously affect the production. In this section, we focus on the analysis of EMR signals of the four rock bursts.

Fig. 8 shows the EMR signal curve monitored before the rock burst occurred. From the figure, it is obvious that: (1) before the rock burst, the intensity and pulse number of EMR signal showed a rise trend generally for more than five consecutive days and a good positive correlation; (2) some curves showed a more gentle rise trend (Fig. 8(a)) while others fluctuated violently (Figs. 8(b)~(d)); (3) the rock burst didn't occur at the maximum of EMR signal or at its ascending process, but occurred within 48 h after the EMR signal reached its peak and at lower intensity level.

Although a rock burst suddenly occurs, it generally experiences 4 stages including breeding, development, initiation, and termination. The process always accompanies with the generation of



(a) 5.25 rock burst (b) 6.18 rock burst

(c) 7.27 rock burst (d) 8.21 rock burst

Fig. 8 EMR signal curves before rock bursts with time from May to August, 2011

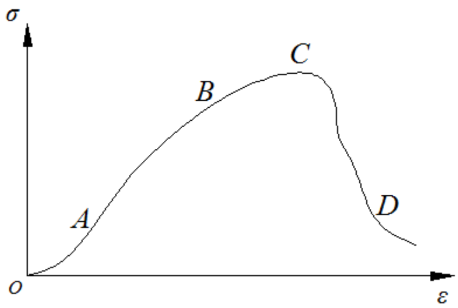


Fig. 9 The entire stress - strain curve of gas-bearing coal under loading

large amount of fractures in coal rock mass and the emission of a large amount of EMR signals. EMR signal curves shown in Fig. 8 are similar in shape to the stress-strain curves of coal sample under the confining pressure shown in Fig. 9. It can be seen that similar to the failure of coal, the in situ instability and failure of coal rock mass also undergo the compaction stage (OA), the linear elastic deformation stage (AB), the plastic deformation stage (BC), and the macroscopic failure stage (CD). Before Point C, with the stress increasing, the strength and frequency of micro-fractures inside the coal rock mass continuously increase, and simultaneously the intensity and pulses amount of EMR signals also consecutively increase, which has been proven by the aforementioned experimental results.

As a typical heterogeneous anisotropic material, instability and failure inside the coal rock mass are closely associated with its own homogeneity. A high homogeneity means similar strength of the voxels inside the coal rock mass and their spatiotemporal uniformity at failure and represents a slow increase of EMR signals during the rock burst disaster evolution. While a low homogeneity corresponds to a greater difference in voxel strength. Therefore, at lower applied load, those voxels will first crack, resulting in emitting a large amount of EMR signals within a very short time and subsequent possible signal valley. Only when the externally applied load is high enough to damage those voxels with greater strength, they are concentratedly damaged within a short time. In this case, the macroscopic performance of EMR signals is a fluctuating growth. Taking into account the complicated structure inside underground coal rock mass, the presence of small faults and other geological defects greatly reduces its homogeneity, so EMR signal most rises in a fluctuating manner before the occurrence of rock burst.

When loading enters the middle and late stages, especially the post-peak stage, microfractures in coal mass reduce rapidly due to self-organizing regulation of continuous converging and coalescing and gradually form large-scale macroscopic fractures, eventually resulting in occurrence of unstable rock burst. The reduction in EMR signals in this process is mainly due to decline of microfractures frequency, indicating that they step into the process to gradually coalesce into large or macroscopic fractures and lead to unstable coal rocks and failure. Therefore, sudden decline of EMR signal after arriving at a greater value does not mean relief of rock bursts risk, rather forebode a major unstable damage even a rock burst disaster. This is our main conclusion obtained during our long-term on-site EMR monitoring and forewarning of rock bursts.

4.4.2 Sensitive indicators

The analysis of a large amount of EMR signal data found two parameters worth of concern. One is the rate of change in the data sequence, which can be used to predict aftermath evolution of rock burst hazards; the other is the maximum of the data sequence, which is the key for us to forewarn rock bursts. The procedure for finding the two parameters is as follows: (1) draw the data sequence trend line, that is the line connecting the turning points of data starting to rise and starting to decline and able to most reflect the ascending trend of the data sequence, as shown as the red line (intensity) and green line (the number of pulses) in Fig 8. (2) Calculate the rate of baseline change according to Eqs. (1) and (3) find the maximum of the line.

$$\eta = \frac{B - A}{t} \times 100\% \tag{1}$$

where A is the starting point from which the line trends upward, B is the maximum of EMR signals along the line, and t is the time with hour as its unit. Table 1 gives the intensity and pulse number indicators of measured EMR signals.

From Table 1 it can be seen that both the maximum and change rate of EMR signals are relatively concentrated. Before rock bursts occurred, there are 3 EMR signals greater than 150 mV, and 3 signal change rates greater than 1. Although the maximum pulse value and pulse number are more discrete, there are 4 maximal pulse values greater than 3000.

We found that ranks of EMR signal indicators sensitive to rock burst in a descending order is maximum EMR intensity > rate of changes in EMR intensity > maximum value of EMR pulses > rate of change in amount of EMR pulses. In practical applications, the EMR intensity indicators including maximum EMR intensity and rate of changes in EMR intensity should be used as the major warning parameter, and the number of pulses as the reference indicator. Table 2 lists the specific warning criteria for rock bursts using EMR indicators.

Table 1 Intensity and pulses amount indicators of EMR signals measured in situ

	Intensity		Amount of pulses	
	Max. (mV)	Rate of change	Max.	Rate of change
5.25 burst	117	1.02	3 030	48.84
6.18 burst	156	0.57	4 500	23.44
7.27 burst	155	1.77	3 590	68.50
8.21 burst	152	1.14	4 850	57.74

Table 2 EMR indicator forewarning criteria for rock bursts

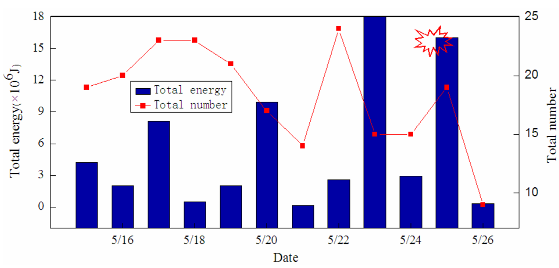
<table>
<tr><th rowspan="2">Forewarning indictor</th><th rowspan="2">Sensitive indicator</th><th colspan="2">Critical value</th><th rowspan="2">Forewarning method</th></tr>
<tr><th>Level 1</th><th>Level 2</th></tr>
<tr><td rowspan="2">EMR Intensity</td><td>Max value (mV)</td><td>100</td><td>150</td><td rowspan="2">Issue the first early warning when any one of the sensitive indicator reaches the level 1 critical value; Issue the second early warning when any one of the sensitive indicator reaches the level 2 critical value</td></tr>
<tr><td>Rate of change</td><td>0.5</td><td>1.0</td></tr>
<tr><td>Amount of EMR pulses</td><td colspan="4">As the reference indicator, when it continuously rises but the EMR intensity indicator has not yet reached the Level 1 early warning value, it is necessary to pay closely attention to changes in the indicator</td></tr>
</table>

4.4.3 Microseismic verification

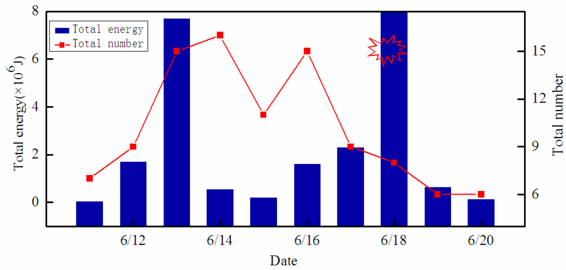
Microseismic monitoring technology, as an effective means for mine seismicity research, has been drawn great concern of researchers at home and aboard and the mining industry. Analysis of microseismic signals produced in the coal rock damage and fracture process real-time monitor the internal stress state and spatial fracture morphology of stope coal rock, roof activities and their released energies (Young *et al*. 1989, Mao 2005, Li *et al*. 2007). Thus, microseismic technology has been widely applied for mine focal source location and dynamic disaster monitoring and forecasting.

Qianqiu coal mine uses the ARAMIS M/E microseismic monitoring system (Poland EMAG company) to real-time monitor the whole mine. To validate our results, we analyzed the energies and frequencies of microseismic events occurring at the whole 21141 Face area within 7 to 10 days before the 4 rock bursts (Due to too many events, events with higher than 103 J were included). Fig. 10 shows the energies and frequencies of microseismic events occurring at the whole 21141 Face area within 7 to 10 days before the 4 rock bursts studied above.

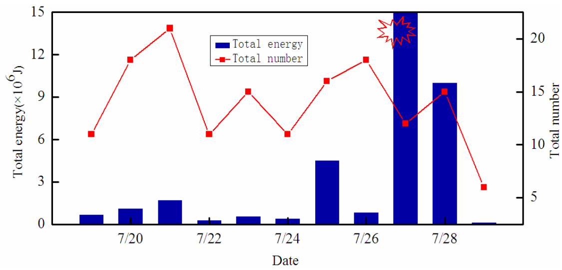
It is obvious from Fig. 10 that before rock bursts occurred, total energies and frequencies of microseismic events showed similar characteristics of EMR signals, that is: (1) first increases before decrease; and (2) rock bursts happened at the lower level of the descent process. Yamada *et al*. (1989) and Rabinovitch *et al*. (1995) believed that acoustic emission (microseismic) and electromagnetic emission from loaded coal rock masses are a homologous heteromorphic issues. The common characteristics of EMR and microseismicity show that EMR could better reflect the evolutionary process of the "elastic deformation-plastic deformation-plastic failure" of underground coal rock masses prior to rock bursts, and implementation of early-warning according to variation features of EMR is effective and feasible.



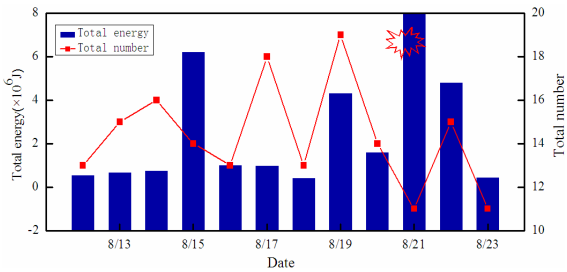
(a) 5.25 rock burst



(b) 6.18 rock burst



(c) 7.27 rock burst



(d) 8.21 rock burst

Fig. 10 Energies and frequencies of microseismic events occurring at the whole 21141 Face area within 7 to 10 days before the 4 rock bursts studied in the study

5. Discussion

Through the analysis of the EMR data above, we find that before rock burst occurs, monitored EMR indicators such as its intensity and pulses amount are well and positively correlated, generally showing a rising trend for more than 5 continuous days either slowly or dramatically, and the disaster bursts generally occurs at the lower intensity level within 48 h after reaching its peak intensity. The rank of EMR signals sensitive to rock bursts in a descending order is maximum EMR intensity > rate of change in EMR intensity > maximum amount of EMR pulses > rate of change in the amount of EMR pulses.

The monitoring and early warning of rock burst mainly depends on 2 points: (1) the field geological conditions. Different conditions may induce disasters with different mechanism, so we have to analyze the geological effects, such as part 4.1. (2)The performance of monitoring equipment. This section briefly discusses the basic properties and the development direction of the monitoring method we proposed.

At present, our developed EMR monitoring instrument aims to detect and analyze EMR signals of 3~500 kHz. Thus, its monitoring scope or distance could be calculated according to the following formula (Wang 1997)

$$L = \sqrt{\frac{\rho}{\pi \mu f}} \tag{2}$$

where L is the effective propagation distance of electromagnetic wave, f is the frequency of EMR, ρ is the resistivity of coal, which generally changes in the range of 10^2-10^3 Ω·m (Jaeger *et al.* 2007); and μ is the relative conductivity with value often taken as $\mu = 4\pi\times10^{-7}$ H/m (Martinez-Vega

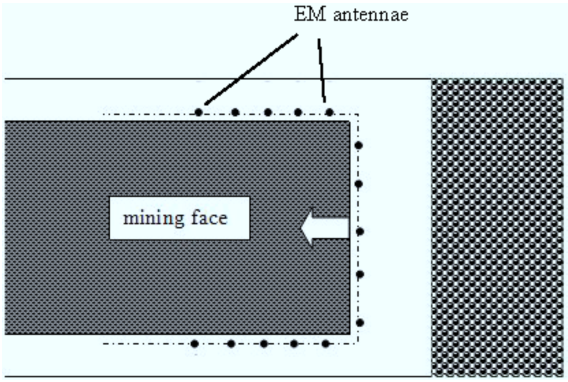


Fig. 11 Schematic of multiple EMR signal antenna arrangement

2013). Thus, the monitoring distance of this instrument is relatively smaller and in the range of 7~22 m. In other words, the EMR monitor can only be used to measure the deformation and fracture state of coal rock masses in this range. If the focus of rock bursts is farther away from the monitor, the evolutionary process of rock bursts won't affect or propagate to the detection range, thus, the measured EMR signal would be normal. To solve this problem, it is necessary to take the two following measures.

(1) Developing ultralow frequency EMR signal antenna

According to Eq. (2), the EMR frequency is inversely proportional to its propagation distance in the coal rock mass. Therefore, without considering the effects of coal rock geological structure and heterogeneity, the use of lower frequency antenna can receive the EMR signal generated by further coal rock fracture. At the same time, considering that under the coal mine environment, interference sources mainly are high frequent ones generated by the starting and stopping of working machines, as well as generated by high-power generators or motors, while the development of ultra-low frequency EMR signal monitor is favorable for the enhancement of the system capability for resisting interference. Therefore, developing ultralow frequency EMR signal monitor and corresponding signal antenna is an important means to increase the EMR monitoring distance and avoid interference.

(2) Implementing local multi-antenna monitoring

As shown in Fig. 11 antennas were laid out along the face roadway at every certain distance (for example, 50 m). Their received signals were comprehensively analyzed using a multi-channel host machine. Such arrangement not only can avoid the problem that a single antenna is incapable of receiving EMR signals due to farther distance from the focus of rock burst, but also enable to detect the spatial evolution characteristics of rock burst disasters through different antenna measurement signals.

6. Conclusions

Before rock burst occurrence, inside the coal rock mass subject to external stresses there is a breeding process for stress accumulation and energy concentration that always goes with the whole deformation and failure process of coal rock structure, making it possible monitoring and forewarning rock bursts from the angles of coal rock deformation and failure, as well as fractures development.

The principle using EMR for monitoring and early warning rock bursts can be summed up as follows: (1) stress concentration in the coal rock causes it to crack, emitting a large amount of EMR; (2) when the measured EMR level reaches a certain intensity, which reveals that deformation and fracture inside the rocks have become serious, rock burst instability may occur anytime and it's necessary to implement an early warning.

Before rock burst occurs, monitored EMR indicators such as its intensity and pulses amount are well and positively correlated, generally showing a rising trend for more than 5 continuous days either slowly or dramatically, and the disaster bursts generally occurs at the lower intensity level within 48 h after reaching its peak intensity.

The rank of EMR signals sensitive to rock bursts in a descending order is maximum EMR intensity > rate of change in EMR intensity > maximum amount of EMR pulses > rate of change in the amount of EMR pulses. In practical applications, EMR intensity should be used as the major forewarning parameter, the maximum intensity and its changing rate as the sensitivity indicators, and the amount of pulses as the reference indicator.

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