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Case Report

Early-Warning Model of Gas Outburst Hazard in Excavation Roadway Based on Microseismic Parameters

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Abstract: In order to evaluate and give a early-warning about the gas outburst risk during excavation, comprehensive indexes used to evaluate the gas outburst risk are put forward and a gas outburst early-warning model based on the normal distribution function (2σ) is created; a typical working face with gas outburst risk in Xinzhuangzi Mine of Huainan Mining Area is selected as the object of tracking and monitoring, and a microseismic monitoring system is created to track and monitor comprehensively the destruction process, destruction degree, and distribution of the coal mass ahead of the tunnel during excavation; the gas outburst risk is evaluated according to the monitoring data and using the comprehensive gas outburst risk evaluation indexes and early-warning model, and a timely and effective early warning about the gas outburst risk is given; the gas outburst indexes are used to check the effect of the gas outburst risk evaluation and early warning. The results show that the microseismic monitoring technology can provide reference for gas outburst evaluation and early warning; the comprehensive gas outburst evaluation indexes and the early-warning model (2σ) can reflect the variation trend of the outburst risk, accurately and effectively evaluate and give an early warning about the outburst risk during the excavation, and optimize the advance gas drainage drill hole design parameters to improve the gas drainage ratio, thus providing effective guidance for taking risk removal measures and ensuring safe and rapid tunnel excavation.

Keywords: Outburst Hazard, Excavation Roadway, Evaluation Index, Early-Warning Model, Microseismic Monitoring Technology

1. Introduction

Typically, a gas accident is closely related to the working face of the mine (excavation tunnel, coal-revealing rock tunnel, coal working face, and the above works controlled by the geologic structure belt), and the main reasons for such an accident are as follows: during an excavation with a gas outburst risk, excavation disturbing force, etc. resulting in quick coal stress transfer and constant elastic energy accumulation so that stress concentration areas are formed and there is a stress difference between the coal and the excavation space [1, 2, 3]. Because the plastic flow in the coal is short and its dissipated energy decreases, however, the accumulated energy cannot be effectively released. As a result, the coal is very likely to be damaged so as to induce the gas accident. Especially when there is a geologic structure such as a fault or a fold ahead of the excavation tunnel, which inevitably has an impact on the continuity of the coal seam, as coal seam thinning or breaking, the gas flow channels will be obstructed to result in the higher gas pressure and increase the risk of incurring a gas dynamic disaster to a degree [4, 5]. In case of frequent gas outbursts in the excavation tunnel, the lives of the workers are put in danger and high-cost and low-speed coal excavation severely restrict mining alternation as well as mining safety. As the mine's excavation depth increases and the gas outburst risk increases more and more severe during the excavation, shortcomings such as restricted scope, highly repeated measures and high time cost are gradually revealed during the implementation of gas outburst measures such as loosening blasting, advance drainage drilling, and combined drainage while excavating [6, 7, 8]. So, it has important theoretical and practical significance to carry out studies on the analysis, evaluation, and early warning of working face coal and gas outburst risk of coal mines that is rich in gas.

Currently, there are many engineering practice records but only a few theoretical studies and simulation tests in the aspect of coal excavation tunnel risk analysis. There are fewer real-time dynamics monitoring and early warning studies [9, 10, 11]. Because the microseismic monitoring technology can identify the actual processes of coal or rock fractures and determine the locations of the microfractures in the 3D space, it is possible to carry out real-time dynamics monitoring and early warning by using the distribution of the microseismic events to reflect the destruction and stress variation of the coal ahead. However, a coal/gas outburst accident in a coal mine typically occurs suddenly and disastrously, so its gas outburst risk evaluation and early warning are complex and random [12, 13, 14, 15]. Large amounts of monitoring data reflecting the temporal and spatial coal fractures that can be obtained during the microseismic monitoring test featuring random fluctuations and cannot indicate well the omens and features that tell us any imminent gas outburst risk. So, a related mathematical method needs to reasonably analyze and process the obtained data to reveal the laws in the data and identify the typical characteristic and critical values. Typically, importance has been attached to the mathematical statistics method as a mathematical method of processing the discrete or random data, which has given good results in many aspects [16, 17, 18, 19]. So, it is very necessary for grasping the microseismic law immediately before the gas outburst occurrence to create an appropriate risk evaluation indexes and an early-warning model.

In the study presented by the paper, an excavation tunnel with gas outburst risk in Xinzhuangzi Mine of Huainan Mining Area was monitored for a long time using the microseismic method based on the high-accuracy microseismic theoretical system and technique, an early warning was given on the gas outburst risk evaluation carried out according to the monitoring data and the established outburst risk evaluation indexes and early-warning model, and finally, the effect of the early warning was validated to prove the reliability and feasibility of the early-warning model, thus providing a practical guidance for gas monitoring and control against accidents.

2. Outburst Risk Evaluation and Early-Warning Model

2.1. Determination of Evaluation Indexes

During the test, a microseismic signal is a pulse-type wave signal from which characteristic parameters need to be extracted. Then, the gas outburst risk analysis, evaluation, and early warning are given according to the magnitudes and variation laws of the extracted parameters. Typically, microseismic signals have common characteristic parameters as follows: number of microseismic events, event ratio, total number of events, number of major events, energy, and energy rate. The definitions and features of the above parameters are as follows: number of microseismic events (frequency); microseismic event ratio; total number of events; number of major events; energy; energy rate.

Currently, traditional microseismic data analysis adopts the statistical laws of parameters such as number of microseismic events and energy for disastrous accident evaluation studies, and as a result, time is omitted so as to lead to evaluation inaccuracy or even misjudgment, thus bringing about a considerable hindrance to normal analysis. In view of this reason, an evaluation method based on the event frequency is presented in accordance with the laws and features of the above microseismic parameters and the need for a time effect analysis.

In addition, long-time and short-time comprehensive evaluation indexes are created in order to timely and reasonably analyze and evaluate the system monitoring data [20, 21]. On the one hand, 24h is selected as the long-time index according to the features of the data collection and recording of the microseismic monitoring system; on the other hand, 8h is selected as the short-time index according to the 3×8 working mode on the mining site. Typically, the long-time index involving much data does not tend to be affected by new data but has low sensitivity; the short-time index has low accuracy yet high sensitivity.

2.2. Risk Early-Warning Model

The gas accidents that happen in the areas featuring high gas outburst risk account for only 5 to 10% of all the gas accidents. Most of the gas accidents happen where normal mining occurs and there is a low gas outburst risk. In addition, research data shows that the measured value distribution of the sound emission parameter is very similar to the graph of a normal distribution function. So, a reasonable description of the microseismic parameters monitored is given in this section according to the relation between sound emission and microquake, features of microseismic parameters, and the features of the normal distribution function.

In addition, the features of the normal distribution function are as follows: (1) The area of the standard normal distribution interval [-1, 1] or the normal distribution interval $(\mu-\sigma, \mu+\sigma)$ accounts for 68.27% of the total area; (2) The area of the standard normal distribution interval [-1.96, 1.96] or the normal distribution interval $(\mu-1.96\sigma, \mu+1.96\sigma)$ accounts for 95% of the total area; (3) The standard normal distribution interval $(\mu-2\sigma, \mu+2\sigma)$ accounts for 95.44% of the total area; (4) The area of the standard normal distribution interval [-2.58, 2.58] or the normal distribution interval $(\mu-2.58\sigma, \mu+2.58\sigma)$ accounts for 99% of the total area; (5) The standard normal distribution interval $(\mu-3\sigma, \mu+3\sigma)$ accounts for 99.74% of the total area.

On the basis of the above comprehensive gas outburst risk evaluation indexes and according to the features of the microseismic parameters and the normal distribution function theory, a risk early-warning model is put forward as follows:

In case of $|X_i - \overline{X}| < \alpha \times S$, there is no gas outburst risk (1)

In case of $|X_i - \overline{X}| > \alpha \times S$, there is a gas outburst risk (2)

In which,

X_i — System-monitored instantaneous value of microseismic parameter;

$\overline{X}$ —Overall sample mean of microseismic parameter;

α —Random error range coefficient (2 assigned according to the 2σ principle in normal range);

S —Overall sample standard deviation of microseismic parameter.

3. Analysis of an Engineering Case

3.1. Geologic and Mining Conditions of Monitoring Area

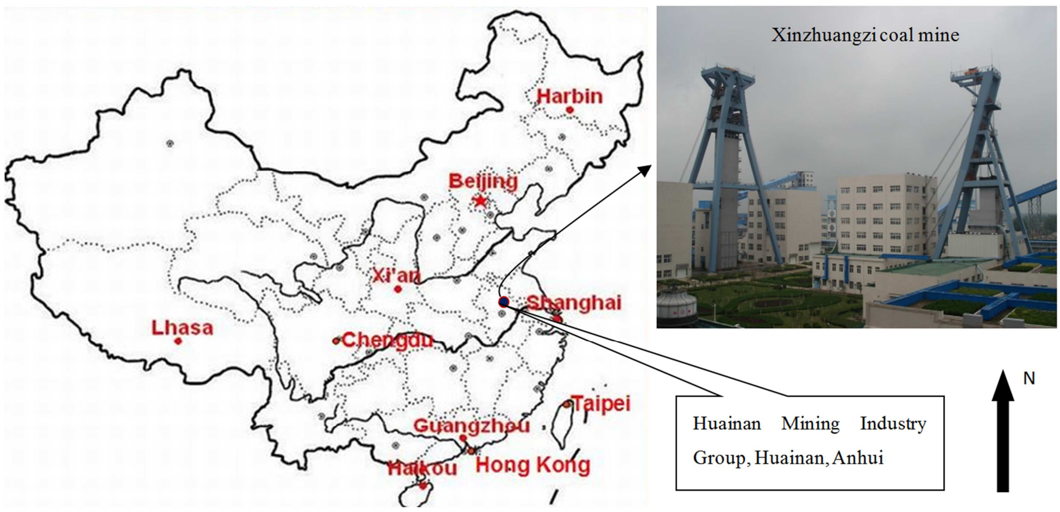
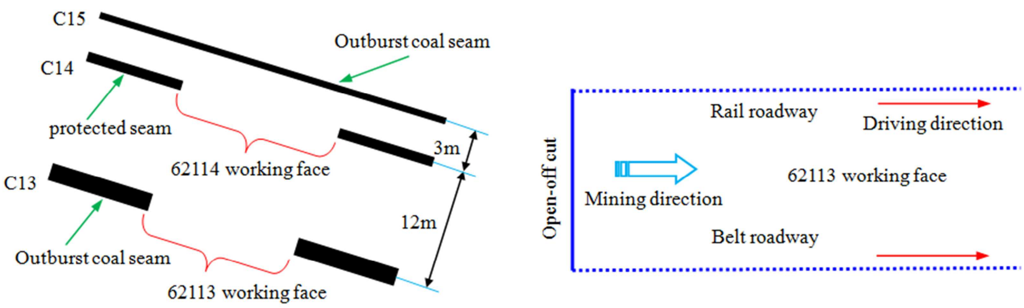


Fig. 1. *Location and layout of coal mine in the Huainan Mining Group.*

Huainan Mining Group is one of the 13 billion tons of coal energy base in China, located in the north central part of Anhui province, as shown in Fig. 1. The gas hazard is very serious in the mining area, the occurrence conditions of coal seam and geological structure are complex, which belong to the severe problem for gas control. And the coal seam is soft, low permeability, high gas content, high gas pressure, so that it is the heavy disaster area of gas explosion accident in China. Xinzhuangzi coal mine of Huainan Mining Group is a typical representative of the high gas coal mine, which is very complicated and characterised by deep overburden (-300 to -1100 m), multi-seams (8 to 15), high methane content (12 to 26 m^3/t), soft coal (f = 0.2-0.8), low permeability (about 0.001 md), high methane pressure (up to 6.2 MPa).

The coal seam C13 of Huainan Mining Area's Xinzhuangzi Mine, with fissures and many faults, is 2.1 to 12.0m thick, 6.16m on average, and its working face 62113 has the strike length of 860m; its upper limit elevation is -590m, its low limit elevation is -665m, and its average dip-direction length is 120m. The coal seam C14 is not stable in occurrence, and it has gas outburst risk; its thickness range from 0.4m to 1.3m, 0.8m on average. The coal seam C15 is 0 to 0.8m thick and is not stable, and its working face 62114 is 900m long in the strike direction; its upper limit elevation is -569m, its lower limit elevation is -650m, its mining height is 1.5m, and its average dip-direction length is 145m. In addition, C15 and C13 are of high gas outburst risk, and the firstly mined protective seam C14 protects C15 and C13. The area has the mining conditions as shown in Fig. 2.



(a) Mining conditions of monitoring area

(b) Sketch of mining conditions in working face 62113

Fig. 2. *Conditions of geologic and mining.*

3.2. Monitoring Plan Design

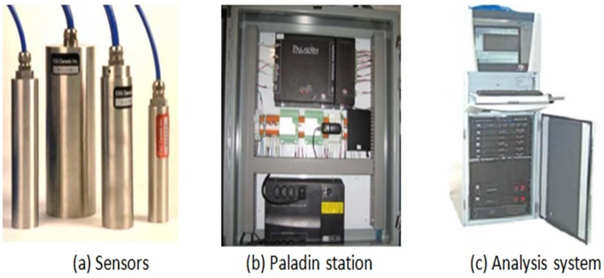


Fig. 3. *Component unit of microseismic moanalysis system.*

The microseismic monitoring system used in this study is divided into three parts: detection sensors, data acquisition instrument (paladin station), host analysis system, as shown in Fig. 3.

After taking into full consideration the monitoring area's stopping scheme, mining plan, and installation difficulty, three microseismic data acquisition instruments are laid out at the work face 62113 and two ones at 62114. The five data acquisition instruments are connected to 30 channel sensors by cable. They are connected in series to send signals to the aboveground computer by fiber to form the microseismic monitoring system [22], as shown in Fig. 4.

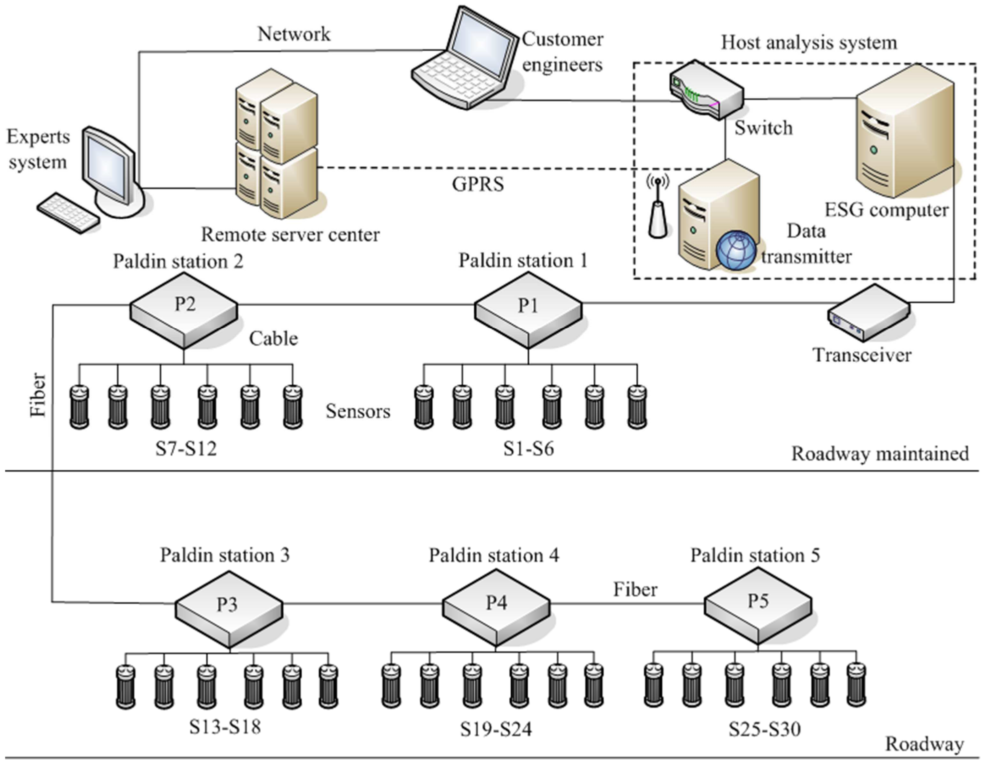


Fig. 4. *Network topology of microseismic monitoring system.*

Furthermore, in order to form a good monitoring array, most of the sensors were arranged in the roadway behind the driving face, and parts were arranged in the roadway maintained of working face. The sensors spacing is about 50~80m, and the local encryption is 20m. Finally, the three-dimensional coordinates of the sensors about this monitoring scheme is as shown in table 1.

Tab. 1. *Three-dimensional coordinates of sensors.*

Installation position	**Acquisition Sub-station**	**Serial number of sensors**	**Three-dimensional coordinates**		
			x/m	**y/m**	**z/m**
62114 Working face	P1	1#	3600.10	7912.60	-575.10
		2#	3643.70	7888.00	-557.20
		3#	3691.80	7859.00	-576.80
		4#	3738.50	7833.10	-574.60
		5#	3780.40	7787.40	-577.90
		6#	3837.70	7724.10	-572.30
	P2	7#	3857.70	7685.50	-649.60
		8#	3883.80	7636.00	-644.70
		9#	3842.60	7767.60	-647.10
		10#	3881.40	7740.60	-649.20
		11#	3926.10	7709.30	-646.90
		12#	3979.30	7672.30	-645.30

Installation position	Acquisition Sub-station	Serial number of sensors	Three-dimensional coordinates		
			x/m	y/m	z/m
		13#	4028.60	7637.50	-658.30
		14#	4115.80	7576.50	-658.70
	P3	15#	4150.10	7552.80	-658.30
		16#	4170.60	7538.70	-658.10
		17#	4242.90	7488.30	-657.40
		18#	4043.20	7549.70	-637.30
		19#	4092.70	7630.30	-580.40
		20#	4334.00	7558.30	-583.90
62113 Working face	P4	21#	4262.00	7605.00	-583.90
		22#	4226.80	7627.30	-584.40
		23#	4109.20	7704.10	-581.30
		24#	4047.50	7747.70	-584.90
		25#	3979.00	7795.20	-655.10
		26#	3932.90	7827.70	-657.90
	P5	27#	3890.50	7857.50	-653.40
		28#	3854.10	7883.10	-656.30
		29#	3814.70	7910.90	-654.70
		30#	3752.70	7954.20	-651.20

3.3. Analysis of Monitoring Results

The microseismic monitoring system is used for the long-term comprehensive tracking and monitoring of the excavations of the working face 62113 and 62114. The destruction process, degree, and distribution of the coal ahead of each tunnel during excavation were monitored to provide references for gas outburst risk evaluation and warning. The microseismic monitoring results of the working face 62113 are as shown in Fig. 5.

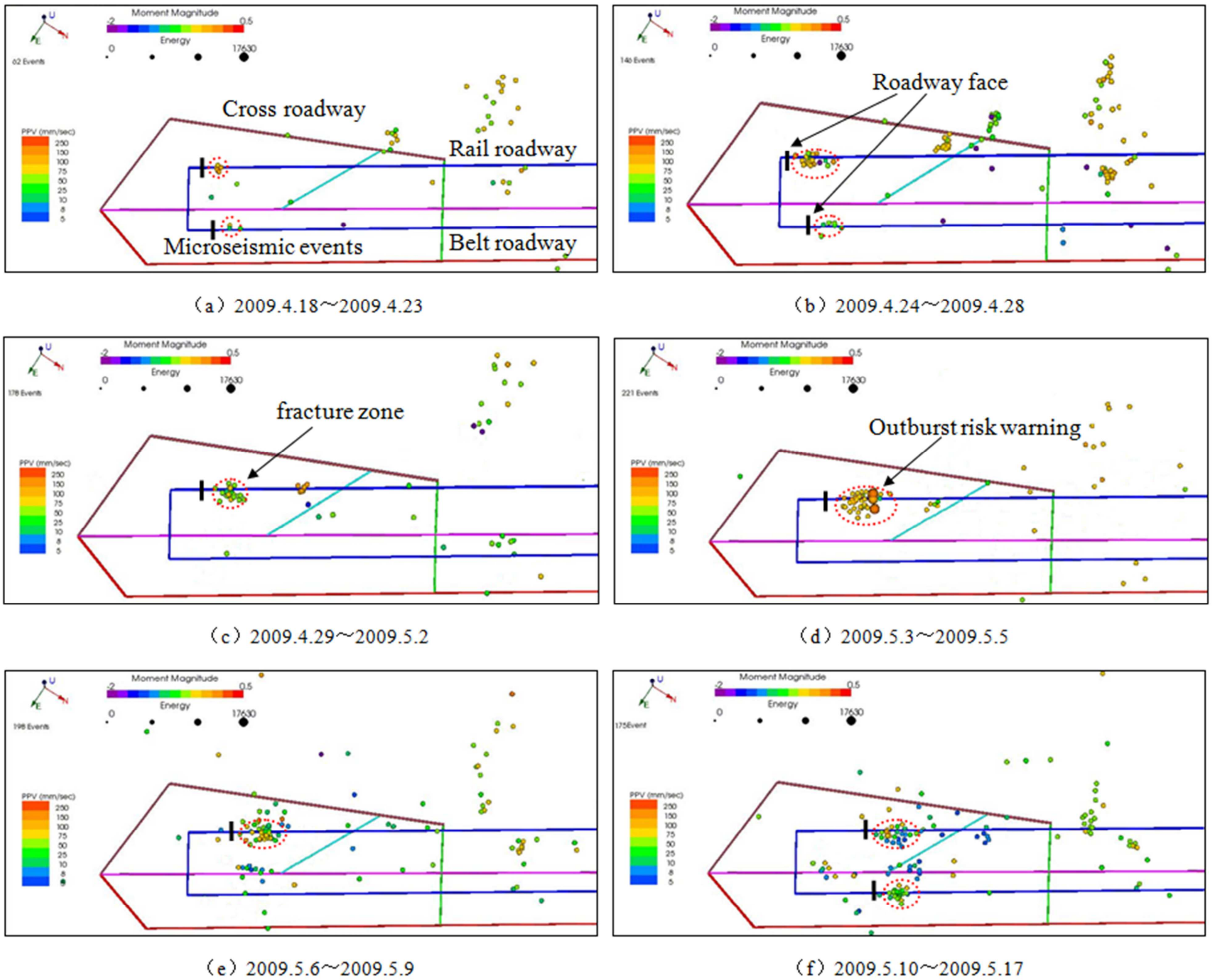


Fig. 5. *Distribution law of microseismic events of rail roadway in 62113 working face (2009.4.18～2009.5.17).*

The above montioned graphics show that since April 18, 2009, the rail roadway and belt roadway had undergone different degrees of destruction, which were signs of microfractures. The reason is that the bearing stress far higher than the coal's uniaxial compressive strength was formed because the self- weight stress of the overburden supported by the coal mass was transferred to the surrounding coal due to the mining disturbance. However, under the action of the shearing stress, the surrounding coal was destroyed, deformed, and flowed to develop a pressure relief belt with a certain length. As a result, the coal's interior has stress concentration areas and microfracture areas of different degrees, and in addition, they continuously migrated and expanded toward the excavation direction into the depths of the roadways. According to the microseismic event data enclosed in the figure, sometimes the rail roadway was severely damaged, and sometimes the belt roadway was so, but generally, the rail roadway was more severely damaged. Especially from May 3, 2009 to May 5, 2009, there were many microseismic events with high frequency and considerable energy and thus with high outburst risk. So, it is necessary to enhance monitoring work and track their evolvement.

3.4. Evaluation and Analysis of Outburst Risk Warning

Site investigation shows that the rail roadway advanced to a position about 140m away from the cutting point from May 3 to May 5, 2009. At 21:13 of May 5, 2009 when side drill holes were drilled for advance gas drainage, the bit resistance phenomenon occurred, and the left upper corner had considerable downward deflection accompanied by scaling off. It can be judged that the phenomena were signs of an imminent outburst. According to the distribution law of the microseismic events, the system detected the anomaly of this position one or two days earlier, an early warning was timely issued after event-based trend identification, 2 σ model evaluation, and critical value comparison. After control measures such as pressure relief, support reinforcement, improved ventilation, etc., the accumulated energy was released, and no gas outburst occurred at this position and the excavation was successfully done through this position. Afterward, fewer events gradually occurred and the energy was sharply decreased until May 17, 2009, and during the period, no dynamic phenomenon was found again.

In order to validate this dynamic phenomenon, the 2 σ early-warning model created above was used to evaluate its risk. Because there are lots of monitoring data collected during excavation, the long-time index L_f (event frequency) was selected as the example to obtain more accurate warning results. Fig. 5 shows that from April 18, 2009 to May 17, 2009, the system had monitored for 30 days. The event frequency each day can be obtained from the database. Its mean value and standard deviation were calculated to determine $\mu+2\sigma$ =79.15, while the event frequency on the date of May 5, 2009 (23rd day) was 101. Then, substitute the above data in the formula $|X_i-\overline{X}|<\alpha\times S$ or $|X_i-\overline{X}|>\alpha\times S$, i.e. $|X_i|$=101> $\mu+2\sigma$ =79.15. It is easy to notice that this dynamic phenomenon has the gas outburst risk. The warning evaluation result is as shown in Fig. 6.

So, the microseismic technology can be used to track and monitor the changes of the coal microfracture information on the real-time basis, deduce the temporal and spatial intensity features of any possible gas outburst accident, and show the optimal timing for giving an early warning about the imminent danger. In addition, the event evaluation indexes and 2 σ early-warning model can reflect the change trend of the gas outburst risk, thus providing effective guidance for giving a warning about any gas accident and taking danger-avoiding measures.

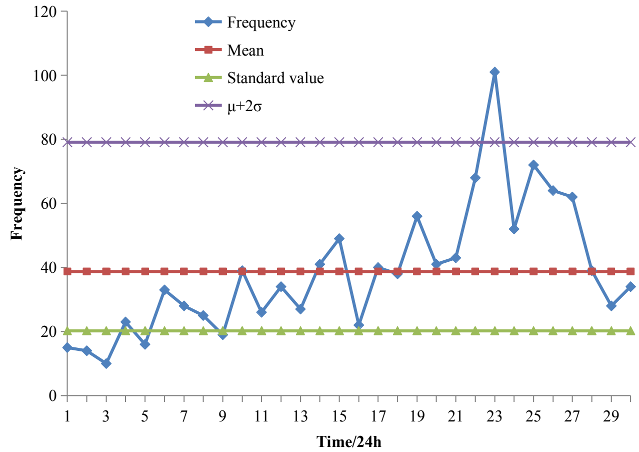


Fig. 6. *2 σ evaluation result of outburst warning by L_f of abnormal position in rail roadway.*

3.5. Early-Warning Effect Validation

In order to validate the correctness of the above early-warning results, two sensitive indexes for gas outburst risk prediction (amount of cuttings S and amount of desorbed cuttings K_1) are used. Their variation laws can reflect the features of the outburst to a degree. Typically, the larger the amount of cuttings S every unit hole length is, the higher the imminent outburst is [23, 24]. However, the K_1 value's physical meaning is the amount of desorbed gas every kilogram of coal sample exposed to the atmosphere within one minute since its coming off the coal mass. Typically, a higher K_1 value means higher gas content in the coal, higher destruction degree, higher gas desorption speed, and higher coal/gas outburst risk [25, 26, 27].

The maximum amount of cuttings and desorbed cuttings data collected from May 18, 2009 to May 17, 2009 when the excavation of the working face 62113 was being performed are selected. Their curves are as shown in Fig. 7. The figure shows that the amount of cuttings on May 5, 2009 (23^{rd} day) = 6.2> 6 Kg/m (critical value according to China's regulations), while the amount of desorbed cuttings on the same date=0.43 > 0.4 $ml/g\cdot\min^{1/2}$ (critical value), indicating that this area will involve coal or gas outburst risk and there was a possibility that such an outburst accident occurred. The S and K_1 values at that moment, however, were still high, and therefore there was still an outburst risk. After an early warning was given and an outburst removal measure was taken, the risk was reduced and the excavation process was safely completed. This also shows that there were dynamic activities at the location but no large-scale outburst accident happened here. So, the sensitive indexes S and K_1 also verified that the area involved the possibility that there were dynamic activities and the results of the outburst risk evaluation are accurate, and proved the correctness and feasibility of the 2σ early-warning results.

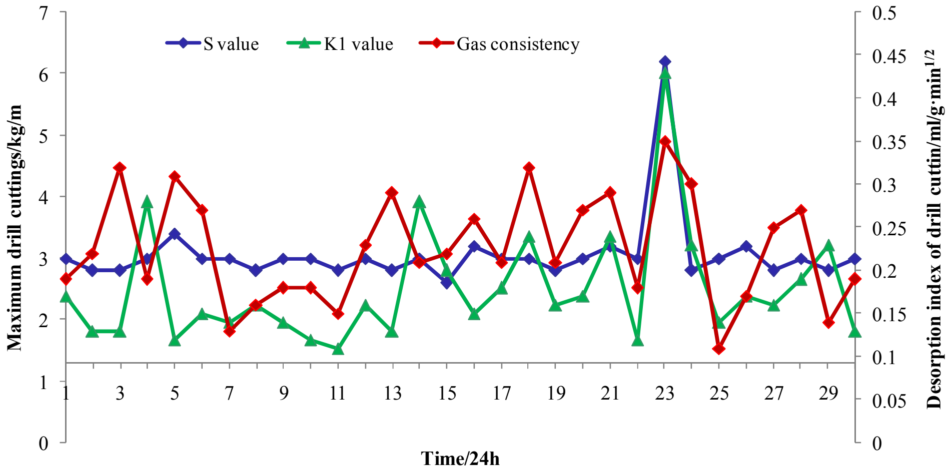


Fig. 7. Change curve of S and K_1 in rail roadway.

In addition, the outburst-removing measure of advance drill hole drainage is typically used in an excavation tunnel, and the outburst-preventing effect is enhanced by increasing the number of drill holes and their depths, thus improving the permeability of the coal mass to facilitate gas drainage, cutting off the gas outburst channels on both sides, intercepting and draining off the gas emitted during the excavation, and forming the protective pressure relief belts in the side walls that can mitigate the coal/gas outburst forces on both sides. However, this method involves long drilling duration, many man-hours, too high gas concentration, and low advance speed. The microseismic data allows for 3D coal fracture location and can determine the loose coal area in the tunnel and the fracture locations and degrees of the coal ahead, thus providing the most dynamic guidance for the optimization of the gas drainage drill hole layout.

4. Discussions

In order to evaluate and early warning the hazard of gas outburst in the process of roadway excavation, the comprehensive evaluation indexes of outburst hazard are proposed based on the theory of microseisms, the 2σ outburst warning model based on normal distribution function is established. Choose typical outburst working face of Xinzhuangzi coalmine in Huainan mining area, through the establishment of microseismic monitoring system, the damage evolution, damage extent and damage distribution of coal in front of working faces in the process of roadway excavation are comprehensively monitored. On the basis of monitoring data, and by use of the outburst hazard comprehensive evaluation indexes and early warning model, the outburst hazard is evaluated, and the timely and effective early warning for outburst hazard is carried on. The effect of outburst hazard assessment and early warning is inspected by use of outburst sensitivity indexes. However, it still needs to be further studied in the following aspects.

Firstly, the sample is short as a result of the number of the early warning model experiment is less, so that the early warning value is single, which has certain effect on the case analysis.

Secondly, the Geiger positioning method is used for the microseismic monitoring system based on residual model of elastic wave, which have some questions about low-efficiency in solving because of the initial value selection isn't appropriate and poor positioning accuracy.

Thirdly, the working face in coal mine is a flattening arrangement, there is no corresponding roadway to install the sensors in the roof and floor of coal seam, so that testing network of the sensors is weak, which is an larger influence on accuracy of Z direction for the monitoring system.

Finally, as the monitoring area is a large scale model, the coal-rock mass is very complicated, and it is relatively difficult to obtain the accurate velocity of coal-rock which participate in positioning calculation. The above parts need to be improved in the next research work.

5. Conclusions

(1). The microseismic monitoring technology can enable the full process and omni-directional monitoring of the destruction process, degree, and distribution of the coal ahead in the tunnel of excavation and thus provide reference for the outburst risk evaluation and early warning.

(2). The comprehensive outburst risk evaluation indexes and the 2σ early-warning model are able to reflect the change trend of the outburst risk and provide the effective guidance for the gas outburst risk evaluation, early warning, and danger-removing measure taking.

(3). The created evaluation indexes and early-warning model are accurate and feasible when used to evaluate the outburst risk and give early-warnings during excavation and can be used to optimize the advance gas drainage drill hole design parameters so as to improve the gas drainage ratio and ensure the safe and quick excavation in the tunnel.

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