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Research Article

Combined Early Warning Method for Rock Burst and Its Engineering Application

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Rock burst is a common mine disaster often accompanied with casualties and property damage. In order to effectively predict and prevent the rock burst occurrence, an effective and accurate method for predicting rock burst is necessary. This paper first establishes the relationship between the drilling cuttings and the releasable elastic deformation energy. However, the traditional drilling cutting method has the defect that the drilling depth cannot reach the stress concentration area and the drilling cuttings cannot accurately reflect the internal stress variation in the deep part of coal body. So, an improved drill cutting method is presented to make up for these defects. Finally, the combined monitoring method based on the improved drilling cutting method and the microseismic monitoring method is established. It not only overcomes the limitations of a single prediction method but also effectively utilizes the advantages of improved drilling cutting method and the microseismic monitoring method. And this combined monitoring method is applied to the No. 3302 coalface of Xingcun Coal Mine. The obtained results indicate that the combined monitoring method can improve the prediction capabilities of the rock burst and provide novel insights for preventing the rock burst occurrence.

1. Introduction

With the mining technology development, the mining depth continues to deepen, and the uncertainty and complexity of geological conditions are becoming more serious, resulting in the frequent occurrence of mine disasters [1–4]. Among them, rock burst is a violent rock failure process and often causes casualties and property damage [5–8]. So, an effective monitoring method for predicting rock burst is very necessary.

In order to study the mechanism of rock burst, lots of experiments, numerical simulations, theoretical analysis, and monitoring techniques related to rock burst have been carried out in recent years [9–11]. Hosseini [12] studied the potential characteristic of rock burst by using passive seismic velocity tomography and image subtraction technique and proved that this method can effectively identify the rock burst prone areas during the mining operation. Sharan [13] predicted the potential occurrence of rock burst based on the finite element model. The effectiveness and efficiency of the proposed numerical technique are demonstrated by comparing finite element results with analytical solutions for in situ stress. Xu et al. [14] proposed the rock burst energy release rate based on the energy theory in order to predict the rock burst. They judged whether the rock burst occurred according to the positive or negative of the rock burst energy release rate and also judged the severity of rock burst according to the magnitude of the rock burst energy release rate. Cai et al. [15], based on the relationship between energy and magnitude of the natural earthquake, predicted the rock burst by a practical example in a gold mine in China. They concluded that the rock burst occurrence must meet corresponding conditions, which are internal geological conditions and external mining conditions. Su et al. [16]

predicted rock burst by acoustic emission characteristics during true triaxial compression of rock. Liu and Wang [17] studied the characteristics of EMR signals induced from fractures of rock samples to predict rock burst. Tang and Xia [18] proposed a seismological method for prediction of areal rock bursts in deep mine based on the seismic source mechanism and unstable failure theory.

Meanwhile, lots of research studies have predicted rock burst based on the drilling cuttings in the field. Qu et al. [19] established the relationship between drilling cuttings, bearing pressure, and coal stress through field measure experiments and numerical simulation methods to predict rock burst. In addition, Gu et al. [20] studied the island coalface based on the drilling effect principle and obtained the critical rock burst index to judge whether rock burst occurred.

However, the method as mentioned above for predicting rock burst is a single prediction method. The theory, technology, and approach of different methods of a single predicting rock burst are different; a single method of predicting rock burst has certain one-sidedness and limitation, and it is difficult to accurately predict whether rock burst will occur [21]. Therefore, considering the limitations of a single predicting method, this paper proposes a combined early warning method for predicting rock burst occurrence using the microseismic monitoring method and the improved drilling cutting method.

2. The Relationship between the Drilling Cuttings and Energy

According to previous research studies, the drilling cuttings' variation curve is very close to the bearing pressure distribution curve of coalface [22, 23]. One of the necessary conditions for the occurrence of rock burst is that the bearing pressure reaches or exceeds the ultimate strength of the coal body [24]. Therefore, it is necessary to study the relationship between stress and drilling cuttings during the mining process.

The drilling cutting method is used to measure the surrounding rock pressure, which is mainly determined by the drilling cuttings discharged from the unit drilling depth during the drilling process. Extensive research studies have shown that the drilling cuttings are mainly composed of two parts: static drilling cuttings and dynamic drilling cuttings [25, 26]. The static drilling cuttings mainly refer to the weight of the coal body in the borehole G_1, which is related to the drilling diameter. The dynamic drilling cuttings mainly refer to the additional drilling cuttings generated by the elastic deformation of the borehole G_2, which is related to the stress state and mechanical properties of the surrounding rock.

The static drilling cutting G_1 is expressed as

$$G_1 = \pi r^2 \rho, \tag{1}$$

where r is the drilling radius (mm) and ρ is the density of coal body (kg/m^3).

The dynamic drilling cutting G_2 is expressed as

$$G_2 = 2\pi r^2 \rho\sigma \frac{1+\mu}{E}, \tag{2}$$

where μ is the coal body Poisson's ratio, E is the elastic modulus of the coal body, and σ is the vertical stress.

So, the total drilling cuttings can be expressed as

$$G = G_1 + G_2 = \pi r^2 \rho + 2\pi r^2 \rho\sigma \frac{1+\mu}{E}. \tag{3}$$

According to the generalized Hooke's law, the elastic strain energy per unit rock under the uniaxial compression test can be expressed as

$$U = \frac{\sigma^2}{2E}, \tag{4}$$

where U is the releasable elastic strain energy of the unit rock body.

According to formulas (3) and (4), the relationship between the drilling cuttings and the elastic strain energy is obtained as follows

$$U = \frac{\left(G - \pi r^2 \rho\right)^2 \cdot E}{2\pi^2 r^4 \rho^2 (1+\mu)^2}. \tag{5}$$

It can be seen from equation (5) that when the drilling diameter and drilling location are determined, the density, Poisson's ratio, and elastic modulus of the coal body are constant, so we can define

$$A = \frac{E}{2\pi^2 r^4 \rho^2 (1+\mu)^2}. \tag{6}$$

Then equation (5) can be expressed as

$$U = A \cdot \left(G - G_1\right)^2 = A \cdot G_2^2. \tag{7}$$

The elastic strain energy increases with the dynamic drilling cuttings, and there is a quadratic function relationship between drilling cuttings and elastic strain energy. The larger the drilling cuttings, the greater the elastic strain energy can be released.

3. Combined Early Warning Method

The gestation process before the rock burst occurrence is often accompanied by various precursor dynamic information. Therefore, the identification of dynamic information can provide a basis for predicting the rock burst. Considering the limitations of applying single monitoring method, this paper establishes a combined early warning method based on microseismic monitoring method and improves drilling cutting method to monitor the dynamic information.

3.1. Microseismic Monitoring Method. The microseismic monitoring, as a type of regional monitoring method, is widely used to predict the rock burst [27]. Microseismic monitoring method is mainly used to record the microseismic time, microseismic energy, and location of the microearthquakes. According to these data, combined with rock mechanics and field geological conditions, the whole process of rock deformation and rock fracture is monitored in real time and three dimensions, which can be used as a basis for evaluating the stability of rock body. Extensive research studies and investigations have conducted that there is a correlation between microseismic energy and microseismic frequency and rock burst [28, 29]. The flow chart for microseismic monitoring is shown in Figure 1.

The operation process of the microseismic monitoring system is as follows:

(1) Firstly, the microseismic sensor installed in the mine can receive the energy vibration signal generated by the rock body rupture, and the vibration signal can be converted into an electrical signal and transmitted to the underground microseismic collecting substation through the communication cable.

(2) Secondly, the underground microseismic collecting substation can transmit the electrical signal to the ground data acquisition server through the communication cable to monitor the rock body rupture, reproduce the microseismic waveform in real time, and automatically process and store the monitoring data.

(3) Thirdly, the ground data processor can collect the microseismic monitoring data from the ground data acquisition server for accurate positioning and energy calculation and analyze the hazard level of the mine monitoring area.

3.2. Improved Drilling Cutting Method. The drilling cutting method, as an effective way of predicting rock burst, is drilling holes in the coal seam to obtain the drilling cuttings to reflect the quantitative relationship between the drilling cuttings and the stress [30, 31]. Following this, critical drilling cuttings of rock burst is ensured, and the danger degree of the rock burst is evaluated. The warning index of drilling cuttings for judging rock burst is shown in Table 1. If the actual drilling cuttings exceed the critical index, there will be the risk of rock burst in the monitored area [32–34].

The expression of drilling cuttings index K is

$$K = \frac{G_2}{G_1}, \tag{8}$$

where G_1 is the normal drilling cutting per meter, which refers to the drilling cuttings at the unaffected area by mining; G_2 is the actual drilling cutting per meter, which refers to the drilling cuttings at the affected area by mining; K refers to the drilling cutting index corresponding to Q; and Q refers to the ratio of the drilling depth to the mining thickness of the coal seam.

According to the above analysis, the critical drilling cutting G_3 can be expressed as

$$G_3 = K_{\mathrm{cri}} \cdot G_1, \tag{9}$$

where G_3 is the critical drilling cutting of rock burst and K_{cri} is the critical drilling cutting index, which refers to the maximum drilling cutting index.

Because of the mining influence, the stress accumulation area in front of coalface is migrated to the deep part of coal body, and the drilling depth cannot reach the stress concentration area; the traditional drilling cutting method cannot accurately predict rock burst. Therefore, based on the drilling cuttings, it is proposed to make use of the variation trend of the drilling cuttings to supplement defect of the drill cutting method to predict the rock burst.

The variation of drilling cuttings is the difference between the drilling cuttings at x_{m} and the drilling cuttings at $x_{\mathrm{m}-1}$ within the unit length, which can be expressed as follows:

$$V = G(x_{\mathrm{m}}) - G(x_{\mathrm{m}-1}), \tag{10}$$

where $G(x_{\mathrm{m}-1})$ is the drilling cutting at $x_{\mathrm{m}} - 1$, $G(x_{\mathrm{m}})$ is the drilling cutting at x_{m}, and V is the actual variation of the drilling cuttings.

The warning index for the variation of drilling cuttings is as follows:

$$V_0 = G_3(x_{\mathrm{m}}) - G_3(x_{\mathrm{m}-1}), \tag{11}$$

where $G_3(x_{\mathrm{m}-1})$ is the critical drilling cutting at $x_{\mathrm{m}} - 1$, $G_3(x_{\mathrm{m}})$ is the critical drilling cutting at x_{m}, and V_0 is the critical variation of the drilling cuttings.

Compared with the actual variation of drilling cuttings and the critical variation of drilling cuttings, when the actual variation of drilling cuttings exceeds the critical variation of drilling cuttings, it indicates that the stress increase rate is faster than normal stress increase rate, and the variation of the elastic deformation energy is greater.

When the drilling cuttings reach the early warning index, but the variation of drilling cuttings does not reach the early warning index, it is considered that there is a rock burst danger. When the variation of drilling cuttings reaches the early warning index, but the drilling cuttings do not reach the early warning index, it is considered that there is a rock burst danger. When the drilling cuttings and the variation of drilling cuttings both reach the early warning index, the pressure relief measures will be carried out.

3.3. The Combined Early Warning Method. According to the characteristics of the above two monitoring methods, a new combined early warning method for rock burst is proposed. The flow chart is shown in Figure 2.

The first step: determining the position of microseismic sensors and boreholes. According to the geological conditions and construction methods of the coalface, the position of the sensors and boreholes should be reasonable and reliable. And it can effectively reflect the variation of microseismic energy and drilling cuttings during the mining process.

The second step: analyzing the data. The related data of microseismic energy and drilling cuttings during the coalface advance process are obtained and analyzed, and the corresponding variation curves are drawn based on the obtained data. Combined with the on-site situation, the abnormal area of the curve is analyzed.

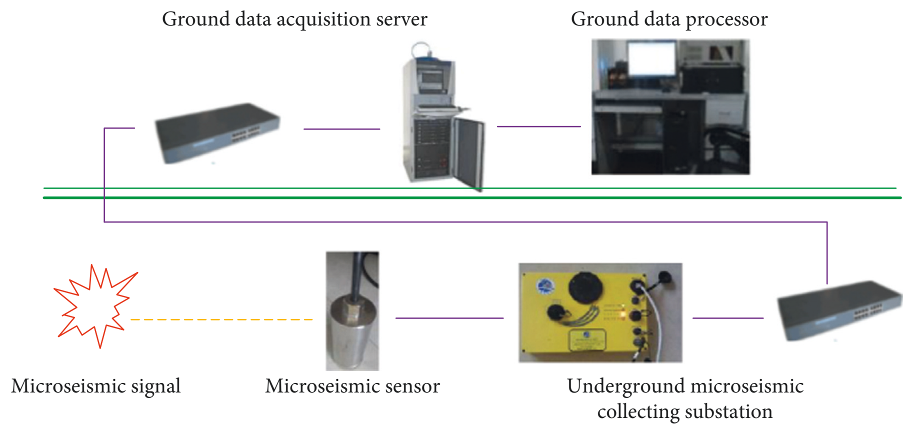

Figure 1: The flow chart for microseismic monitoring.

Table 1: Warning index of drilling cuttings for judging rock burst.

Drilling depth/mining thickness of coal seam (Q)	1.5	1.5~3.0	3.0
Drilling cuttings index (K)	≥1.5	2.0~3.0	≥4.0

The third step: confirming the rock burst warning value. Based on the analysis of the obtained data and the actual situations, the early warning values of microseismic energy, the drilling cuttings, and variation of drilling cuttings can be obtained, respectively.

The fourth step: establishing the combined early warning method. According to the monitoring results of microseismic monitoring and improved drilling cutting method, it is judged whether there is a rock burst danger.

The fifth step: applying the combined early warning method. According to the above analysis, the combined early warning method is applied in the coal mining, and its practicability and efficiency will be discussed in detail.

It is worth noting that the combined early warning method is composed of two predicting methods: the microseismic monitoring method and improved drilling cuttings method. The combined early warning method can show its respective advantages and overcome the corresponding disadvantages and then improve the accuracy of rock burst prediction. At the same time, the rock burst strength can be further predicted according to the corresponding data, microseismic energy, microseismic frequency, drilling cuttings, and variation of drilling cuttings. Compared with the previous research studies, the above two aspects are the main innovation of the combined early warning method.

4. Application of Combined Early Warning Method

4.1. Geology and In Situ Conditions. Xingcun Coal Mine is located in Jining City, Shandong Province, China. No. 3302 coalface in Xingcun Coal Mine is buried at depth of 1190–1280 m, the coal seam dip angle is 1–13 degrees, the average coal seam thickness is 3.5 m, and Platts' coefficient f is 4–6. The roof is 5–20 m thick hard sandstone, and Platts' coefficient f is 6–11. In addition, the lithology of the coal seam and roof of No. 3302 coalface is hard; the fractures overlying hard rock can easily induce dynamic disasters such as rock burst.

4.2. Improved Drilling Cutting Method

4.2.1. Borehole Arrangement. The borehole position is set at the transport grooves and track grooves of No. 3302 coalface. The layout of the boreholes should avoid the fault lines and other geological structures. The drilling diameter is 42 mm, the drilling depth is 12 m, and the interval between the two boreholes is 5 m; the boreholes are arranged in the single row. The distance between the borehole and the floor is 1 m, and the drilling direction is perpendicular to roadway coal wall. Drilling and measurement of the drilling cuttings are performed at morning shift every day. Figures 3 and 4 show the borehole arrangement position and the arrangement method, respectively.

4.2.2. Monitoring Results. According to the above description of the improved drilling cutting method, the variation curve of the drilling cuttings at the unaffected area with the drilling depth is shown in Figure 5. It can be seen that the drilling cuttings at unaffected area by mining increase slowly along with drilling depth, and the function relation between the average drilling cuttings at unaffected area by mining and drilling depth is approximate to one function. However, there is a fluctuation of drilling cuttings at the drilling depth of 9–11 m; it indicates that there is a high stress concentration in this range. And it can be seen that the early warning index of drilling cuttings shows an increasing trend with drilling depth. The drilling cuttings at the unaffected area are lower than the early warning index of the drilling cuttings; this indicates that the stress at the unaffected area by mining does not exceed the critical stress, and there is no possibility of rock burst.

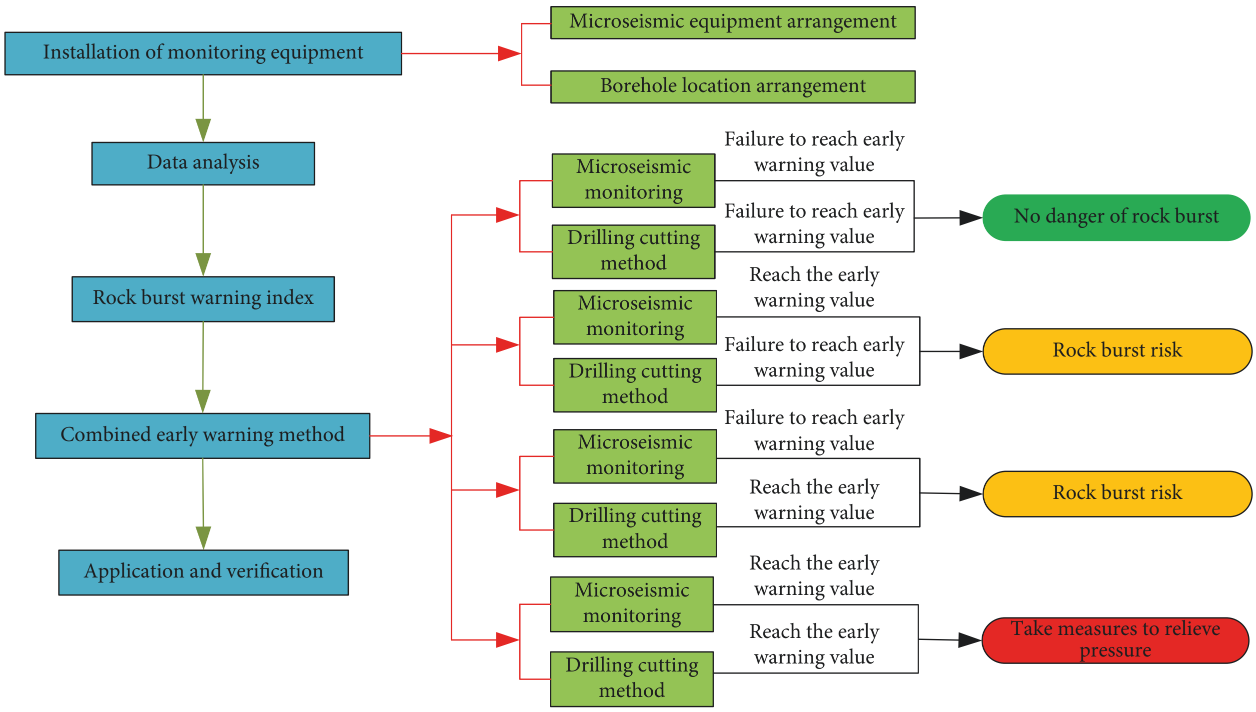

FIGURE 2: The flow chart of the combined early warning method.

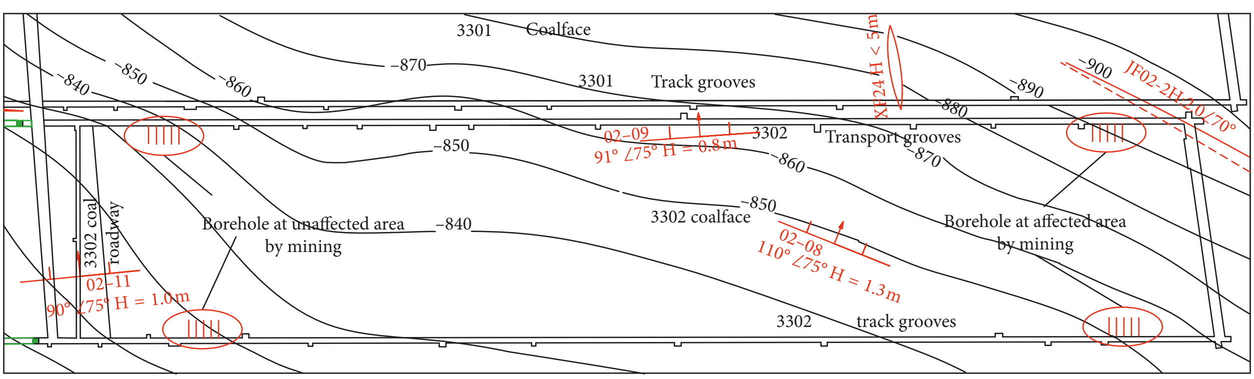

FIGURE 3: Borehole arrangement position of No. 3302 coalface.

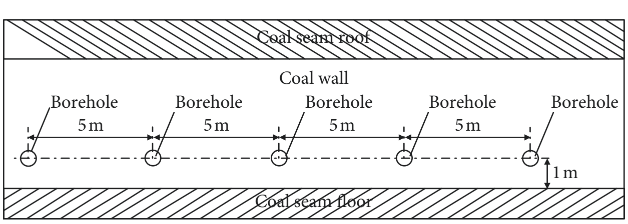

FIGURE 4: Borehole arrangement method.

The variation trend of drilling cuttings at the affected area by mining has been obtained by statistical analysis of drilling cuttings from 5 boreholes in front of the coalface, as shown in Figure 6. There is no fluctuation in the variation curve of the drilling cuttings at the affected area by mining and drilling depth; it indicates that the stress peak in front of the coalface is migrated to the deep part of the coal body due to the mining influence.

However, there are some limitations if only relying on the drilling cuttings to judge the rock burst, which cannot effectively reflect the trend of the stress increasing rate. Therefore, the concept of variation of drilling cuttings method is introduced to compensate for such defects.

In order to study the relationship between the drilling cuttings and the variation of drilling cuttings with the coalface advanced time, the relationship surface figures are drawn separately (Figures 7 and 8).

Figure 7 shows the relationship between the coalface advanced time, the drilling depth, and the drilling cuttings. The drilling cuttings have lots of fluctuations in the No. 3302 coalface mining process, especially in the deep part of the borehole. The drilling cuttings have a large peak on the 24th, 56th, and 87th days; their corresponding weights are 45.96 kg, 79.98 kg, and 65.66 kg, respectively. The time interval between the large peaks of drilling cuttings is about

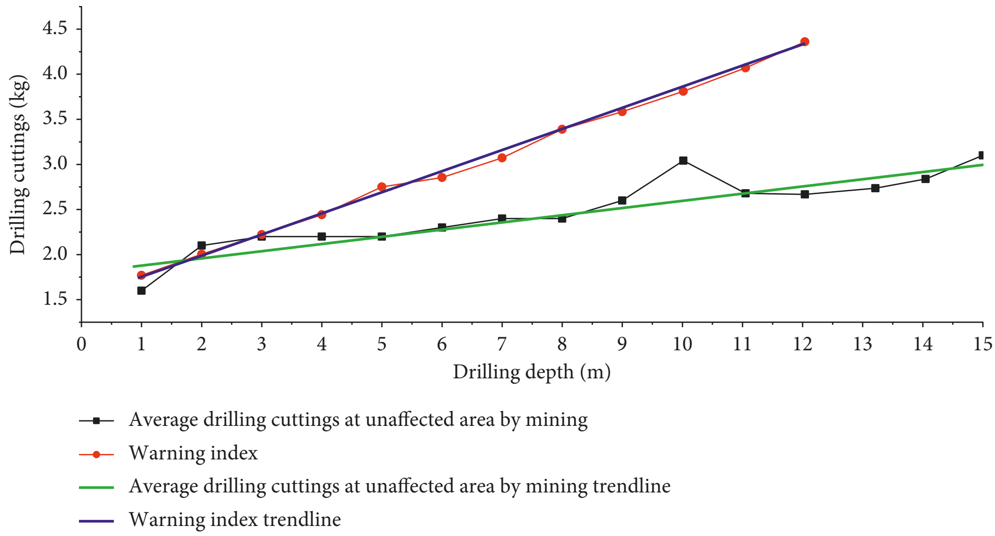

Figure 5: Drilling cutting at unaffected area by mining and drilling cutting warning index.

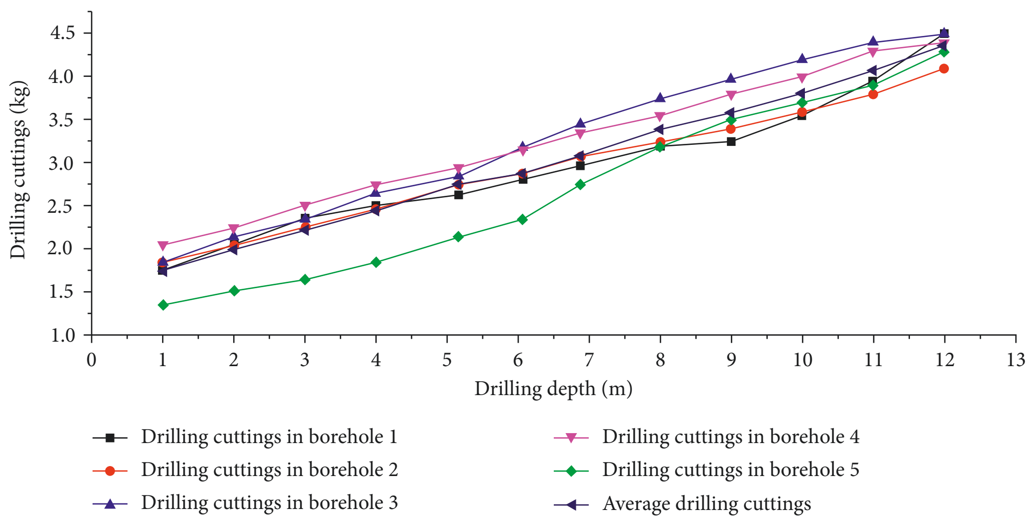

Figure 6: Drilling cuttings at affected area by mining.

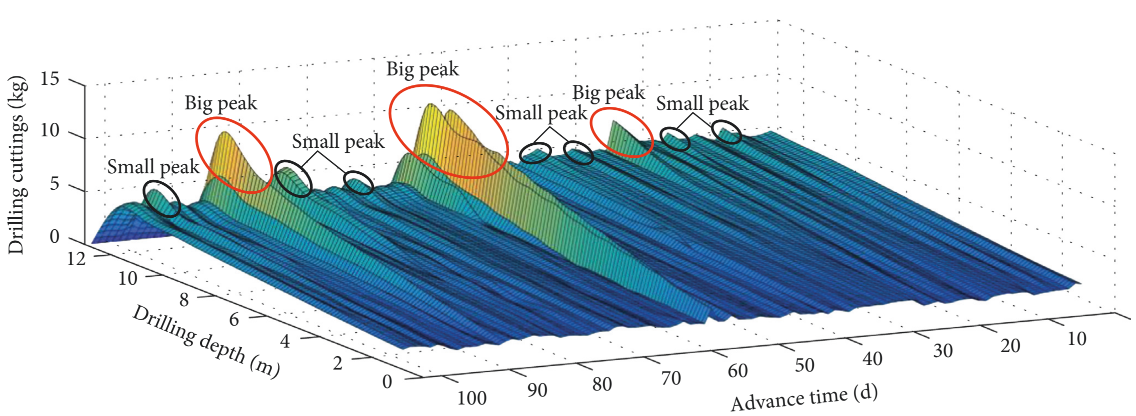

Figure 7: Relationship between the drilling cuttings and coalface advanced time.

30 days. According to formula (9), the drilling cuttings on 56th and 87th days are greater than the warning value of the drilling cuttings, which means there is a risk of rock burst. At the same time, there are some small peaks of the drilling cuttings between the two large peaks, and the time interval between two adjacent small peaks is about 10 days.

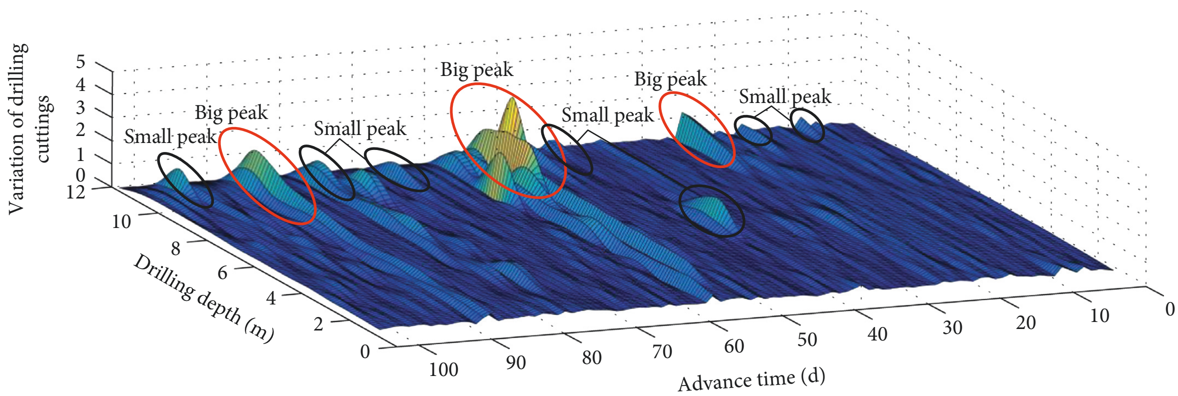

Figure 8: Relationship between the variation of drilling cuttings and coalface advanced time.

Figure 8 shows the relationship between the coalface advanced time, the drilling depth, and the variation of the drilling cuttings. The variation of drilling cuttings also has the fluctuation during the mining process. The peak value of the variation of drilling cuttings is mainly in the deep part of the borehole. According to formulas (10) and (11), the variation of drilling cuttings in the deep part of borehole of the 24th, 53rd, 56th, and 87th days is greater than the warning value of the variation of drilling cuttings. It indicates that the stress increase rate exceeds the normal stress increase rate. The time interval between the large peaks of variation of drilling cuttings is about 30 days, and there are some small peaks between the two adjacent large peaks; the time interval between the small peaks is about 10 days.

Based on the above analysis of drilling cuttings and their variation during the mining process, the time interval of the large peaks is about 30 days, and the time interval of the small peaks is 10 days. It infers that there are large stress concentration and large stress increase rate every 30 days, and there are small stress concentration and small stress increase rate every 10 days.

4.3. Microseismic Monitoring

4.3.1. Arrangement of Microseismic Monitoring System. There is 1 microseismic collector and 4 microseismic sensors in the No. 3302 coalface of Xicun Coal Mine. The microseismic collector is installed on the coal roadway. The 1# and 2# microseismic sensors are installed at a distance of 100 m and 300 m, respectively, from the opening of the transport grooves. The 3# and 4# microseismic sensors are installed at a distance of 100 m and 350 m, respectively, from the track grooves. The arrangement of microseismic collector and microseismic sensor is shown in Figure 9.

4.3.2. The Results of Microseismic Monitoring. Although the microseismic event is different from the rock burst, the activity law of the microseismic events has a significant correlation with the probability of rock burst occurrence. The microseismic monitoring method is used to monitor the microseismic events in the coalface mining process in real time, and the microseismic frequency and microseismic energy are calculated every day. Figure 10 shows the results of microseismic monitoring of the No. 3302 coalface. It can be seen that the time interval between the large peaks of the microseismic energy is about 30 days, and the total microseismic energy peak is 70915 J, 94612 J, and 79721 J, respectively.

From the curve of the total microseismic energy and the microseismic frequency, it can be seen that the rock experiences a period of time to accumulate energy before the rock burst occurs, which is called the silent period. The length of silent period is related to the rock burst occurrence. So the rock burst can be judged by the length of the silent period [35]. It can be seen from Figure 10 that the microseismic energy during the silent period is small, but the number of microseismic occurrences is high. This is mainly because the rock will first generate lots of small fractures before a large fracture occurs. When lots of small cracks are interpenetrating each other, the conditions for generating the large fractures are formed, and rock burst may occur. After the rock burst, the microseismic energy and the microseismic frequency are significantly reduced; this is mainly because the large amount of elastic deformation is released through rock burst, and there is not enough energy to generate new massive fractures.

According to the geological conditions of the No. 3302 coalface, the cause of rock burst is mainly due to the stress concentration influenced by the coalface square, in which the coalface advancement distance is equal to the coalface length. The microseismic energy generated on the 56th day is most intense, which is mainly caused by the large coalface square produced by the No. 3302 coalface and the adjacent No. 3301 coalface. Meanwhile, there are lots of cracks in the surrounding rock of the roadway, and workers at the site heard the sound of rock breaking in the surrounding rock, so there is a greater rock burst risk.

4.4. The Results of Combined Early Warning Method.

According to equation(5), the relationship between the releasable elastic deformation energy, the microseismic energy, and the No. 3302 coalface advanced time is analyzed, as shown in Figure 11. The variation trend of the releasable elastic deformation energy in the drilling depth range is

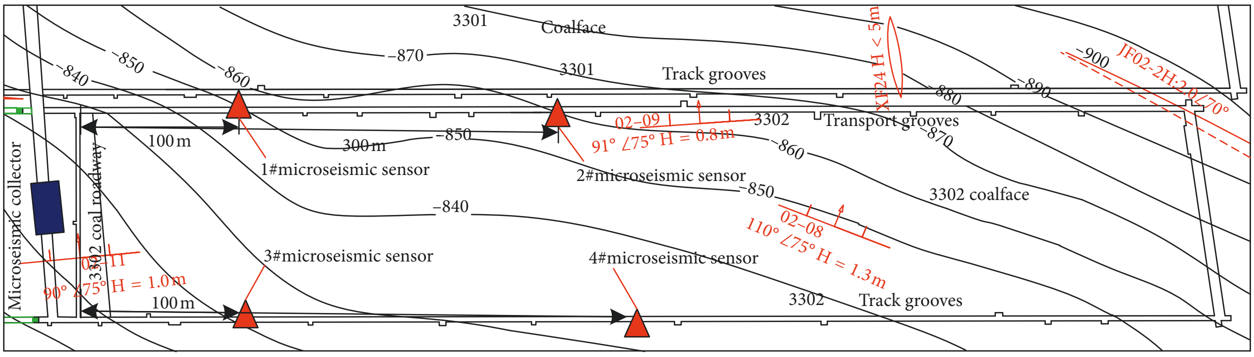

Figure 9: Layout diagram of microseismic collector and microseismic sensor.

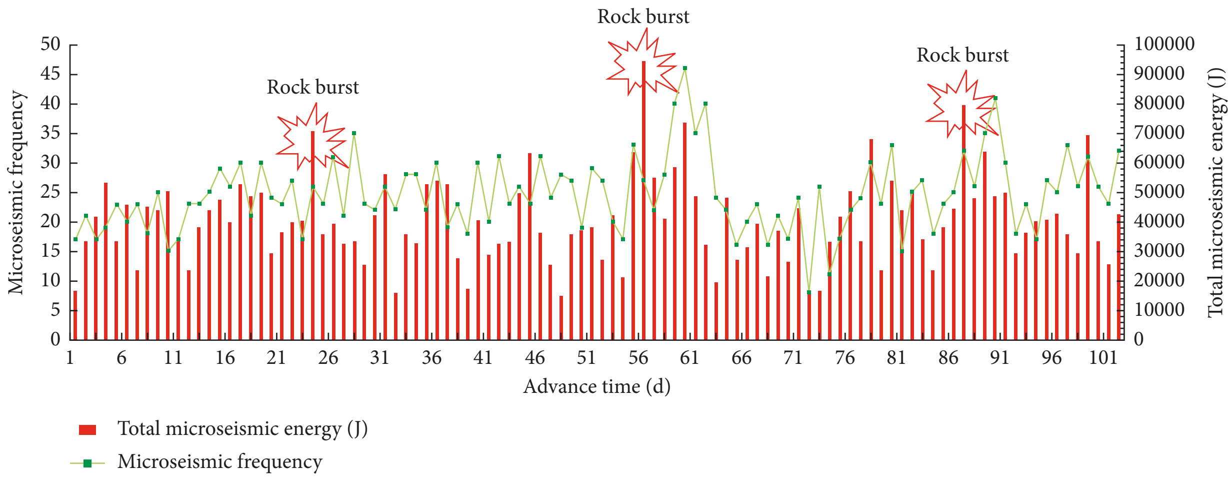

Figure 10: Total microseismic energy and microseismic frequency in mining process.

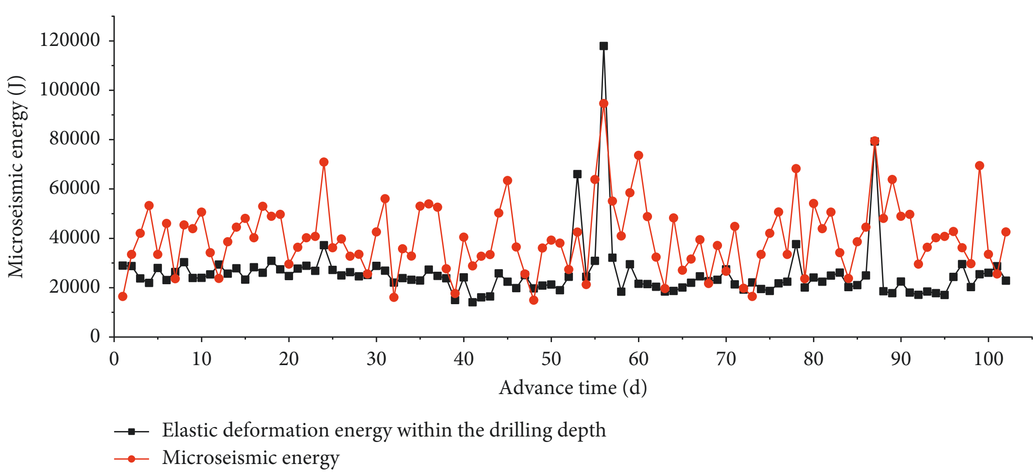

Figure 11: Relationship between the releasable elastic deformation energy and microseismic energy.

similar to the microseismic energy. However, the elastic deformation energy within the drilling depth is lower than the microseismic energy. It indicates that the microseismic monitoring method can reflect the releasable elastic deformation energy outside the drilling depth range. At the same time, the microseismic monitoring method can monitor the location of rock burst and the energy released outward; the improved drill cutting method can effectively reflect the variation rate of the stress and elastic deformation energy.

The results of the improved drilling cutting method show that the small peaks of the drilling cuttings and their variation will appear every 10 days, and the big peaks of drilling cuttings and their variation will appear every 30 days. The microseismic monitoring results show that the big peak of microseismic energy will appear every 30 days. That means the stress, the stress increase rate, and the released elastic deformation energy will increase every 30 days, and there is a danger of rock burst. Among them, the drilling cuttings and their variation and microseismic energy on the 56th day are the largest, exceeding the warning index, so the corresponding pressure relief measures should be taken. This is mainly because of the large square of the No. 3302 coalface, that is, the No. 3302 coalface advancement distance is equal to the sum of the length of the No. 3302 coalface and the No. 3301 coalface.

Therefore, according to the combined early warning method, there will be danger of rock burst every 10 days, and certain pressure relief measures should be taken every 30 days during the No. 3302 coalface mining process.

5. Discussion

The single method of predicting rock burst has certain limitations. It is difficult to accurately determine whether the rock burst will occur. Therefore, this paper proposes two monitoring methods to predict rock burst: microseismic monitoring and improved drilling cutting method, which can complement each other. Meanwhile, the improved drilling cutting method can make up for the defect that the drilling depth could not reach the stress accumulation because the stress accumulation area is migrated to the deep part of the coal body due to the mining influence. The combined early warning method based on the microseismic monitoring and improved drilling cutting method can not only predict the location and energy of rock burst but also predict the variation rate of stress and elastic deformation energy.

However, there are some limitations because these conclusions are obtained by monitoring No. 3302 coalface of Xingcun Coal Mine, and the monitoring conclusions of other coal mines are not yet known. So, it is also necessary to apply and analyze this method to other coal mines in the future.

6. Conclusion

(1) The function relationship between the drilling cuttings and the releasable elastic deformation energy is established. When the geological conditions and the borehole diameter are constant, the function of the drilling cuttings and the releasable elastic deformation energy can be expressed as $U = A \cdot G_2^2$. So there is a quadratic function relationship between the drilling cuttings generated by borehole elastic deformation and the releasable elastic deformation energy.

(2) Based on the traditional drilling cutting method, the variation of drilling cuttings is introduced, which can make up for the defect that the drilling depth failed to reach the stress accumulation due to the mining influence. And the variation of the drilling cuttings can effectively reflect the variation trend of the stress increasing rate. When the drilling cuttings do not exceed the warning value, but the variation of drilling cuttings is beyond the warning value, there is still a risk of rock burst.

(3) Based on the microseismic monitoring method and the improved drilling cutting method, the combined early warning method for predicting rock burst is established, which can avoid the limitations of the single monitoring method. It can make better use of the advantages of microseismic monitoring method and improved drilling cutting method and also can predict the risk of rock burst.

(4) The prediction results of the combined early warning method based on the No. 3302 coalface of Xingcun Coal Mine are consistent with the actual results, which verify the reliability and effectiveness of this method and provide a new way for predicting the rock burst occurrence.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that there are no conflicts of interests regarding the publication of this paper.

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