Research Article

Mechanism of Coal Bursts Induced by Horizontal Section Mining of Steeply Inclined Coal Seams and Application of Microseismic Multiparameter Monitoring in Early Warning

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Coal bursts occurring in steeply inclined coal seams (SICSs) are increasingly severe. To solve this problem, a mechanical model for the distribution of static stress on coal-rock masses along panels and the distribution of dynamic load induced by the breakage of thick and hard roofs with propagation distance was established. The stress characteristics after a superposition of dynamic and static loads on the roof and floor roadways (Rr and Rf) were determined. In addition, precursory information characteristics and index sensitivities of four indices for dynamic loads and the CT index for static loads based on seismic tomography were separately analyzed. The monitoring and warning indices for SICSs and flat seams were compared. The results showed that the static stress of Rr was significantly higher than that of Rf, which provided a basis for the stress-triggering coal burst behaviors. Three indices for dynamic loads and seismic tomography results exhibited remarkable precursory information and high sensitivity. However, the performance of lack of shock index is poor. The continuous anomaly and the contradiction of indices at Rr and Rf can be considered as precursory information for predicting coal bursts.

1. Introduction

The number of coal mines with steeply inclined coal seams (SICSs) accounts for about 5% of all in China [1]. There are more than 100 coal mines with SICSs widely distributed in over 20 mining areas in the Xinjiang Uygur Autonomous Region, Gansu, the Ningxia Hui Autonomous Region, and other areas [2–5]. In recent years, as deep coal seams are gradually mined and the mining intensity constantly increases, coal bursts induced by horizontal section mining of SICSs are becoming increasingly severe. Coal bursts greatly impact personnel safety and mine production. In 2005, 2013, and 2016, coal burst accidents occurred in the Huating Mine in Gansu Province, Wudong Mine in the Xinjiang Uygur Autonomous Region, and Yaojie No. 3 Coal Mine in Gansu Province, respectively, causing casualties and property losses.

Currently, coal bursts in SICSs are increasingly dramatic and scholars have carried out numerous studies from the perspectives of the underlying mechanisms of coal bursts and prevention methods to further understand the generation process of coal bursts. Ju and Li [6] established a model for the fracturing of cantilever beams formed by the strata in the main roof triggered by the section mining of SICSs and deduced the expression for elastic energy in the cantilever beams along the strata in the main roof. Based on the beam theory, Lai et al. [7, 8] constructed a mechanical model for roofs during the mining of SICSs and elucidated their deformation law. They also conducted laboratory tests utilizing
planar combined loading devices to explore the evolutionary characteristics of temperature and acoustic emission (AE) during the fracturing of steeply inclined rock pillars under the effect of coal mining. Lan [9] suggested that the impact force during section mining of two subect extra-thick coal seams was generated from the crowbar effect of the rock pillars at the two sides of a gob on the coal mass. If the rate of stress change applied on the coal mass by the force source satisfies the stress exponent of dynamic failure of the coal mass, a coal burst occurs. In terms of prevention and control of coal bursts, Yu et al. [10] determined the effect of mining and tunneling of the upper and lower sections of working faces as the main inducement for coal bursts in roadways by analyzing influencing factors of coal bursts in the Yanbei Coal Mine in China. By long-hole blasting in roofs and pressure release blasting for coal masses, coal burst risk can be effectively reduced.

The purpose of exploring the mechanism of coal bursts is to further understand the process of coal burst behaviors during horizontal section mining of SICSs. Investigating prevention and control measures aims to reduce the danger in burst-prone areas and to avoid or mitigate the occurrence of accidents. Monitoring and warning are made to predict or find burst-prone areas in real time by utilizing advanced technologies based on the understanding of the burst generation process. Therefore, monitoring and warning is particularly important for mitigating dynamic disasters such as coal bursts in the field.

In recent years, with the development of new technologies, monitoring and warning for coal bursts has been the focus of much research. Microseismic (MS) monitoring for dynamic and static stresses is increasingly being explored by researchers. Based on the analysis of MS monitoring data, a number of indices for evaluating rock burst tendency have been proposed regarding statistical features and source mechanism parameters for individual rock burst incidents. Tang and Xia [11] used apparent stress/volume and b value, both of which are concerned with the MS magnitude in an underground copper mine. Lu et al. [12] and Wang and Cai [13] used indices covering both magnitude (total/maximum MS energy, total fault area, b value and Z value) and temporal distribution in underground coal mines. Along with indices for magnitude and temporal distribution, Dai et al. [14] also considered MS spatial distribution in evaluating the recorded MS events in an underground powerhouse. Cai et al. [15] developed a methodology for rock burst forecasting involving the use of a fuzzy comprehensive evaluation model to assess the MS indices, which allows for a more quantitative evaluation of the likelihood of a rock burst incident.

Currently, the impact mechanism of SICSs has not been clearly explained, and there are few studies on the monitoring and warning of SICSs. Under the special coal burst mode of SICSs, whether the conventional monitoring indices can meet the warning needs, whether they are the same as those in the flat seams, and whether the indices have high sensitivity and clear precursor information are yet to be fully determined. For these reasons, this paper aimed to theoretically analyze the distribution characteristics of dynamic and static loads in SICSs, monitor and warn the dynamic and static loads, respectively, based on the mechanism, and investigate and select the warning indices with clear precursor information. Overall, this study attempts to give a novel idea to prevent and control coal bursts.

## 2. Mechanism of Coal Bursts Induced by Horizontal Section Mining of SICS

### 2.1. Superposition of Dynamic and Static Loads

A number of studies and field cases have shown that when the static load of the surrounding coal and rock mass, and the dynamic load induced by mining-induced earthquake are superposed and exceed the critical load of bursting, coal-rock mass tends to be destroyed by dynamic force. This results in a dynamic disaster of coal bursts, which has been previously reported [16, 17].

\[
\sigma_s + \sigma_d > \sigma_{b, \min},
\]

where \(\sigma_s\) is the static stress in the coal-rock mass, \(\sigma_d\) is the dynamic stress induced by the tremor, and \(\sigma_{b, \min}\) is the critical stress required for a coal burst.

### 2.2. Distribution Characteristics of Static Stress of Coal Rock in a Coal Mine Panel

The stress state of coal and rock determines whether impact failure will occur. Under the influence of occurrence structure, stresses on the roof and the floor sides of a coal mine panel in the same horizontal slices are quite different in the SICS. For a specific slice, it is mainly affected by self-weight, abutment pressures \(\sigma_r\) and \(\sigma_f\) on the roof and floor sides, pressure \(P_r\) of overlying rock mass scattered in gob, and abutment pressure \(P_f\) of coal mass on the bottom. A mechanical model was built, as shown in Figure 1. The coal mass was divided into a triangle coal zone on the roof (I), a rectangular coal zone (II), and a triangle coal zone on the floor (III) [18].

The stress of bottom coal was determined by stresses on the roof, the floor, and the scattered overlying rock blocks. As scattered overlying rock blocks are in a stable state for a certain period of time, it slightly changes stress in the working face. To simplify the calculation, it was considered that \(P_r\) is uniformly distributed over the coal body. As demonstrated in Figure 1(b), stress of the OC side shows lateral stress distribution of the panel. In the figure, the \(xOy\) Cartesian coordinate system was established along the horizontal and vertical directions with the vertex of the slice at the lower left corner as the origin. Where, \(L\) and \(h\) represent the length (m) and the height (m) of the slice, respectively. “AE” is the boundary of the triangular zone on the roof, and “\(\theta\)” represents the dip angle (°) of the coal seam.

Stress in the triangular zone on the roof is illustrated in Figure 1(c). To simplify the calculation, it was considered that the AE boundary is subjected to uniformly distributed stress \(\sigma_{z, 1}\), while \(OE\) side bears the abutment pressure \(P_{z, 1}\) of the bottom coal, and the OA side bears uniformly distributed abutment pressure \(\sigma_r\) of the roof. Moreover, \(F_{z, 1}\) and \(G_{1}\) represent the frictional force between the roof and the
coal mass and gravity of the triangular zone on the roof, respectively.

\[ G_1 = \gamma_c h \cot \theta, \]  

(2)

where \( \gamma_c \) indicates the average volume force (kN/m\(^3\)) of coal mass and generally values 14 kN/m\(^3\).

Based on stress model in Figure 1(c), a static equilibrium equation of the triangular zone on the roof is shown as follows:

\[
\sigma_r = \left( \frac{2c \cdot \cos \phi}{1 - \sin \phi} + \frac{1 + \sin \phi}{1 - \sin \phi} \left( \frac{1}{2} y L \sin 2\theta + \frac{P_f}{\sin \theta} \right) \right) e^{2f ((h/sin \theta) - (x/cos \theta))/L \sin \theta} (1 + \sin \phi/1 - \sin \phi),
\]

(4)

where \( f \) indicates the frictional coefficient between the roof and the coal mass. Stress distribution equation [19] of \( \sigma_r \) is presented as follows:

\[
\begin{aligned}
\int_0^{(h/sin \theta)} \sigma_r \cos \theta dl_{OA} - \int_0^{(h/sin \theta)} \sigma_r \cdot f \cos \theta dl_{OA} - \sigma_{x1} \cdot h &= 0, \\
\int_0^{\lambda cot \theta} P_f dx - \int_0^{(h/sin \theta)} \sigma_r \sin \theta dl_{OA} - \int_0^{(h/sin \theta)} \sigma_r \cdot f \sin \theta dl_{OA} - G_1 &= 0,
\end{aligned}
\]

(3)

According to Formulae (3) and (4), it can be obtained that the abutment stress \( P_{f1} \) of bottom coal in the range of \( OE \) is
Horizontal stress $\sigma_{x1}$ is demonstrated as follows:

$$\sigma_{x1} = \int_0^{(h\sin\theta)} \sigma_x \cos \theta (1-f) \, dx$$

Stress in the triangular zone on the floor is shown in Figure 1(e). It is considered that $CF$ boundary is subjected to uniformly distributed stress $\sigma_{x2}$, while the $CD$ side bears nonuniformly the distributed abutment pressure $\sigma_f$ of the floor. Moreover, $P_f$, $F_{x2}$, and $G_2$ represent the overburden stress in gob, the frictional force between the floor and the coal mass, and the gravity of the triangular zone on the floor, respectively.

According to the calculation results in reference [20], the stress on the bottom plate $\sigma_f$ can be expressed as

$$\sigma_f = \dot{\sigma}_{CD} = \gamma H_{CD} \cos \theta + \lambda \gamma H_{CD} \sin \theta.$$  

The static equilibrium equation can be established in the horizontal direction:

$$\sigma_{x2} \cdot h = \sigma_f \sin \theta \cdot \frac{h}{\sin \theta} + \sigma_f \cdot f \cos \theta \cdot \frac{h}{\sin \theta}$$

Substitute equation (7) into equation (8)

$$\sigma_{x2} = \frac{(\gamma H_{CD} \cos \theta + \lambda \gamma H_{CD} \sin \theta) \cdot (\sin \theta + f \cos \theta)}{\sin \theta}.$$  

Stress in the rectangular coal zone is demonstrated in Figure 1(d). Coal mass was subjected to horizontal stress $\sigma_{x1}$ and $\sigma_{x2}$ on the left and right sites, shear stress $\tau_{xy}$ in coal mass, and self-weight $G_2$. The equilibrium equation for solving the stress of the rectangle yield is presented as follows:

$$\begin{aligned}
\frac{\partial \sigma_x}{\partial x} + \frac{\partial \tau_{xy}}{\partial y} + X &= 0, \\
\frac{\partial \sigma_y}{\partial y} + \frac{\partial \tau_{xy}}{\partial x} + Y &= 0, \\
\tau_{xy} &= -(c + \sigma_y \tan \phi).
\end{aligned}$$

According to the literature [21], abutment stress $P_{f2}$ of the bottom coal mass and shear stress $\tau_{xy}$, in coal mass caused by horizontal stress $\sigma_{x1}$ and $\sigma_{x2}$ of the rectangular zone within $EC$ range could be obtained as follows:

$$\begin{aligned}
P_{f2} &= \frac{(h \sin \theta)}{\beta} \sigma_x + \frac{c}{\tan \phi} e^{\left(\frac{(h y - 2 \tan^2 \phi)}{2} \beta \tan \phi \frac{(L - x)}{\tan \theta}\right)} + \gamma h \left(L - \frac{h}{\tan \theta}\right) , \\
\tau_{xy} &= - \left(\left(\frac{1}{\beta} \sigma_x + \frac{c}{\tan \phi} e^{\left(\frac{(h y - 2 \tan^2 \phi)}{2} \beta \tan \phi \frac{(L - x)}{\tan \theta}\right)} + \gamma h \left(L - \frac{h}{\tan \theta}\right) \tan \phi + c\right),
\end{aligned}$$

where $\beta$ represents the lateral pressure coefficient on the plane where the ultimate strength is found and $\beta = \mu / (1 - \mu)$ ($\mu$ means Poisson’s ratio). By combining Formulae (4), (5), (6), (9) and (11), the distribution of the abutment pressure of the coal mass in the panel was obtained as follows:

$$\begin{aligned}
P_{f1} &= \int_0^{(h \sin \theta)} \sigma_x \sin \theta (1+f) \, dx + \gamma h^2 \cot \theta, \quad 0 < x < \frac{h}{\tan \theta}, \\
P_{f2} &= \frac{(h \sin \theta)}{\beta} \sigma_x \cos \theta \left(1-f\right) \, dx + \frac{c}{\tan \phi} e^{\left(\frac{(h y - 2 \tan^2 \phi)}{2} \beta \tan \phi \frac{(L - x)}{\tan \theta}\right)} + \gamma h \left(L - \frac{h}{\tan \theta}\right), \quad \frac{h}{\tan \theta} < x < L.
\end{aligned}$$

Figure 2 demonstrates the curve of the stress distribution function of the panel obtained according to Formula (12). The dip angle $\theta$ of the coal seam is set as $60^\circ$ and the height $h$ of a slice is $17.2$ m. The working face is $60$ m in length $L$. Moreover, Poisson’s ratio $\mu$, frictional coefficient $f$, cohesion $c$, and the angle $\phi$ of internal friction separately are set to $0.325, 0.5, 3.62$ MPa, and $33^\circ$.

As shown in the figure, under the effects of roof stress, static stress of $R_f$ lives up to $27$–$44$ MPa, which is obviously greater than that ($10$–$14.5$ MPa) of $R_f$. Coal burst hazards are
more serious under $R_r$, pure static loads. High static stress of the $R_r$ provides the basis of static loads for coal bursts.

2.3. Distribution Characteristics of Dynamic Stress Released by Roof Breakage. During top coal caving in horizontal slices of the SICSs, large quantities of coal could be mined out. When noncritical strata, like the immediate roof were thin, the caving roof showed a low filling degree to gob and a large free space was left in the mined-out space. Consequently, the hard key strata were suspended, thus forming an upturned structure of cantilever beam, as demonstrated in Figure 1(a).

Assume $L_r$, $h$, $q$, and $\omega$ separately represent the length, thickness, self-weight load, and deflection before the breakage of key strata.

In accordance with the research [18], the accumulated energy when the cantilever beam fractures is

$$U = \int_0^{L_r} \omega q \cos \theta dx = \frac{(q \cos \theta)^2 L_r^5}{20EI}$$

(13)

Based on the previous research results [20, 22], the relationship between the dynamic load applied on a certain point in mining space and energy released from roof breakage is expressed as follows:

$$\sigma_d = 0.0645 \rho \cdot C \cdot U^{0.3566} \cdot l_{d0}^{-\eta}$$

(14)

where $\rho$, $C$, $l_{d0}$, and $\eta$ indicate the medium density, the propagation velocity of shock waves, the distance between a certain point and the hypocenter, and the attenuation coefficient of shock waves.

For Formula (14), the medium density $\rho$, the velocity $C$ of shock waves, the length $L_r$ of the main key stratum, the main roof breakage, and the uniformly distributed stress $q$ are 2,500 kg/m$^3$, 4,000 m/s, 150 m, 32 m, and 12.5 MPa, respectively. Moreover, the dip angle of the roof ($\theta$) is 60°, and the attenuation coefficient ($\eta$) is 1.1, respectively. The distances $l$ from the hypocenter of the main key stratum and the main roof to the coal seam are 40 m and 20 m, respectively. Given the above parameters, the distribution curve of the dynamic stress with propagation distance could be obtained, as shown in Figure 2. By combining with Formula (11), the distribution curve of the superposed dynamic and static stress of coal and rock in the working face was obtained.

Based on the distribution curve of dynamic stress, it can be seen that the dynamic load attenuates fast in the transfer process. When the hypocenter is close to the roadway, the disturbance is large; otherwise, the disturbance is small. Due to special occurrence structures of the SICSs, the floor is less significantly fractured and the dynamic load mainly comes from the roof.

3. Monitoring and Warning Indices

According to the mechanism of coal bursts induced by horizontal section mining in SICSs, the force source causing the coal burst mainly includes dynamic and static loads. Therefore, to perform effective monitoring and warning, it is necessary to intensively monitor the force source and the carrier. Thus, a comprehensive warning system is formed, which takes dynamic and static loads as the subject of monitoring, and roof and floor roadways as the object of monitoring.

Based on scholars’ research on monitoring and warning of coal bursts and analysis of MS indices, a great number of indices (e.g. $b$ value and MS activity) for coal burst proneness are used to predict the occurrence probability of coal bursts.
Among the monitoring and warning indices for dynamic loads, \( b \) value and lack of shock \( b \) value belong to negative anomaly indices, which means that the lower the values are, the higher the risk of coal bursts; fault total area, MS activity, and total stress equivalent are positive anomaly indices, which means that the larger these values are, the higher the risk of coal bursts.

For seismic tomography, the index for static loads, according to its formula and partition of risk level, the higher the coefficient of anomaly of wave velocity within inversion region is, the higher the static stress and thus the larger the risk of coal bursts [25–29].

### 4. Case Studies

In previous researches on the SICSs, the contents related to monitoring and warning were not involved. To show the difference of SICSs and flat seams, the section separately took the coal burst behaviors occurring in SICSs and flat seams as an example. The monitoring and warning indices for dynamic loads and seismic tomography results for static loads before and after the occurrence of a coal burst were compared. On this basis, the research attempts to judge whether the indices used for predicting the coal burst risk of flat seams can also be applicable for SICSs and whether precursory information delivered by warning indices for SICSs differs from that of flat seams.

#### 4.1. Basic Conditions of the Panels

##### 4.1.1. Horizontal Section Mining in SICSs

The long wall (LW) 5521-20 panel was located in the No. 5 mining area where 19 slices had been mined. It was in the 20th slice with a burial depth of about 500 m. The panel extended 1,020 m along the strike and the inclination angle of the coal seam was 45–62° with an average of 55°. The slice of the panel was 17.2 m in thickness. To facilitate ventilation and transportation, three systems with lengths of 395, 365, and 260 m were arranged for the panel, as shown in Figure 3.

The average thickness of the coal seam in the LW5521-20 panel was 54.77 m. For the overlying strata on the roof of the coal seam, the lithologies of the main roof and the main key stratum were both oil shale with average thicknesses of 6.68 and 43.88 m, respectively. As for the underlying strata on the floor of the coal seam, the immediate floor was 1.0 thick and consisted of carbon mudstone. The main floor was 1.99 m thick and was composed of gritstone.

##### 4.1.2. A Fully Mechanized Coal Mining Method of Full-Thickness Mining of Flat Seams

The LW11-3102 fully mechanized panel was the second panel of the Menkeqing Coal Mine, in which the minable region had a length of 5539.3 m, a width of 300 m, and a burial depth of about 700 m. At the eastern side of the working face was the LW11-3103 panel (the tunneling was completed but mining had not started), and the LW11-3101 panel (about 2000 m ahead of the LW11-3102 panel), which was about to be mined, was located at the western side. In the LW11-3101 panel, the chain pillar had a width of 35 m. The distribution of the panels is shown in Figure 4.

The 3-1 coal seam in the LW11-3102 panel was mined. The average thickness of the coal seam was 4.75 m, and the dip angle of the coal seam approximated to 0°. The immediate roof and the main roof of the panel separately consisted of siltstone and fine sandstone, respectively. The average thicknesses of these areas were 4.7 and 17.68 m, respectively. The immediate and the main floors also comprised siltstone and fine sandstone, with an average thickness of 10.29 and 21.9 m, respectively.

#### 4.2. Monitoring Measures

SOS and Aramis MS monitoring system were separately installed in Yaojie No.3 and the Menkeqing Coal Mine, which can realize real-time, dynamic, and automatic monitoring of MIT signals in mines. Through data processing, the time, energy, and the spatial three-dimensional coordinates of tremors with energy larger than 100 J can be accurately calculated. On this basis, the type of each tremor was determined and the force source causing a coal burst was judged, thus further evaluating the risk degree for the occurrence of coal bursts in mines. There were a total of 14 geophones distributed around the Yaojie No.3 coal mine and five were close to LW5521-20, including Nos. 4, 5, 6, 7, and 8 (Figure 3). In the Menkeqing Coal Mine, 13 geophones were distributed, in which S1–S4, T8, and T9 were installed around the working face (Figure 4).

#### 4.3. Coal Burst Occurrence

##### 4.3.1. Coal Burst Occurrence of the LW5521-20 Panel

On 29 June 2016, a coal burst with an energy release of \( 2.2 \times 10^7 \) J occurred in the \( R_c \) of the LW5521-20 panel, 49 m away from the open-off cut of the 2# system and 35 m ahead of the mining position of the panel, as demonstrated in Figure 3(a). There were no geological structures like faults and folds around the location where the rock burst occurred. The section 414–430 m away from the open-off cut in roof roadway showed heaved 0.5 m. The sides of the roof heaved 0.2–0.5 m and some anchor rods were broken. Moreover, the fracture was 0.6–0.8 m away from the borehole wall.

##### 4.3.2. Coal Burst Occurrence of the LW11-3102 Panel

From September to December, 2017, 20 coal bursts occurred during the mining of the LW11-3102 panel, which all occurred within the tail entry. On March 3, 2018, a coal burst with an energy release of \( 1.0 \times 10^7 \) J first occurred in the tail entry of the LW11-3102 panel after the MS monitoring system was installed, during which the panel was 810 m away from the open-off cut. Moreover, within the tail entry 120 m ahead of the panel, a single prop was bent and the wood crib was tilted because of being stressed; some anchor nets fell off and the coal mass burst out.
Table 1: Monitoring and warning indices and meanings.

| Name of index       | Formula for index | Index meanings                                                                                                                                 |
|---------------------|-------------------|-----------------------------------------------------------------------------------------------------------------------------------------------|
| b value             | $\lg N (\geq M) = a - bM$ | $M$ denotes the magnitude of an earthquake; $N (\geq M)$ refers to the number of earthquakes with the magnitude not lower than $M$; $b$ reflects the level of intensity of mining-induced tremors (MITs). |
| Lack of shock b value | $b = (0.4343/(M_{\text{mean}} - M_{\text{min}}))$ | $M_{\text{mean}}$ and $M_{\text{min}}$ denote the average energy level within statistical time frame and the initial energy level, respectively. |
| MS activity         | $S = 0.117\lg(N + 1) + 0.029\lg(1/N)\sum_{i=1}^{N}10^{1.5M_i} + 0.015M$ | $N$, $M_i$, and $M$ refer to the total number of tremors, the energy level, and the maximum energy level, respectively. A strong MIT appears after $S$ value is strengthened theoretically. |
| Total stress equivalent | $Q_{\text{32}} = \left(\sum \sqrt{E_i}/ST\right)$ | $E_i$, $S$, and $T$ represent the energy (J) of the $i$th MS event within the statistical region, the area ($m^2$), and the statistical time (day), respectively. |
| Seismic tomography  | $A_n = ((v_p - v_p^0)/v_p^0)$ | $v_p$ and $v_p^0$ refer to the $P$-wave velocity (m/s) at a certain point and the average wave velocity (m/s) within the inversion region, respectively. |

![Figure 3: Layout and profile of the LW5521-20 panel. (a) Layout of the LW5521-20 panel. (b) A-A profile.](image-url)
4.4. Multiparameter Monitoring Results and Analysis. According to the occurrences of coal bursts, the location results were analyzed based on data on MS events (>10^3 J) from June 4 to July 14, 2016, within the LW5521-20 panel. The coal bursts occurred only within the Rr. Therefore, to make the data more comparable, the analysis region was divided into roadway zones at the roof and floor sides, as shown in Figure 5(a). For comparison and analysis, location analysis was performed based on data on MS events (>10^3 J) from February 1 to March 5, 2018, within the LW11-3102 panel. Similarly, the analysis region was partitioned into zones of the tail entry and the head entry, as shown in Figure 5(b). According to the monitoring and warning indices for dynamic and static loads proposed in Section 3, the change trends of the indices before and after the coal bursts in the two panels were analyzed, and the results are displayed as follows:

4.4.1. b Value. Figure 6(a) shows the variation curve of the b value for MS events from June 4 to July 14, 2016, in the 5521-20 panel. As shown in the figure, the b value in the Rr was generally lower than that in the Rf, and the overall trend of the b value was similar. According to the definition of the b value, it can be seen that the coal burst risk of the Rr within the whole monitoring period was higher than that of the Rf. The b value decreased before a MS event with a large energy occurring in the roadway zones at both the roof and floor sides. Before June 26, the b value of the Rr was stable and fluctuated within a small range. The b value of the Rr cyclically changed almost every 10 days. From June 27, the b value of the Rr suddenly and sharply decreased and dropped to 0.346 when the coal bursts appeared on June 29. The b value of the Rf slowly increased during this period. These changes indicated that the Rf at this stage experienced significant MS activity and so macrofracturing likely occurred in the thick and hard roofs to release dynamic load. Within the Rf, MS activity did not significantly occur. Due to the overall change and sudden decrease of the b value before the coal burst behavior, the b value can be used as precursory information.

Figure 6(b) shows the variation curve of the b value for MS events from February 2 to March 6, 2018, in the 3102 panel. It can be seen from the figure that the b value of the head entry significantly changed almost every 10 days. Although the b value of the head entry slightly declined during the coal burst behavior, it increased within the stage on the whole, which conformed to its change period. The b value of the tail entry insignificantly fluctuated within the range of 0.42–0.75. Before the coal bursts occurred, the b value of the tail entry constantly decreased, implying that there was a high coal burst risk within the period, providing explicit precursory information.

The b value of the LW3102 panel showed an obvious difference compared to that of the LW5521-20 panel. There was a similar change trend of b values in Rr and Rf when no coal burst occurred in the LW5521-20 panel; however, the change trend of the b value of the Rr was opposite to that of Rf when the coal burst occurred. The coal burst risk reflected by the b value was contradictory. In contrast, the b value of the head entry in the LW3102 panel followed its period of change. During the coal bursts, the head entry was not significantly affected by the risk state at the side of the tail entry and so the correlation between the two roadways was relatively low.

4.4.2. Lack of Shock b Value. Figure 7(a) shows the change curve of the lack of shock b value. The overall value of the Rr was lower than that of Rf, which implied that the coal burst risk at the roof side was higher. Before the coal bursts occurred, the lack of shock b value within the Rr remarkably declined. However, the coal bursts did not occur in the zone. In contrast, the coal bursts occurred in the Rr, where the lack...
Figure 5: Location results of MS events (>10^3 J) before coal burst behaviors. (a) Location results of MS events in the LW5521-20 panel from June 4 to July 14, 2016. (b) Location results of MS events in LW11-3102 panel from February 1 to March 5, 2018.

Figure 6: Variation curve of b value. (a) LW5521-20. (b) LW11-3102.

Figure 7: Variation curve of lack of shock b value. (a) LW5521-20. (b) LW11-3102.
of shock $b$ value was not significantly changed without precursory information indicating a coal burst. Thus, the lack of shock $b$ value cannot be regarded as a warning index for coal bursts occurring in the SICSs.

As shown in Figure 7(b), different from the LW5521-20 panel, the lack of shock $b$ value dramatically reduced at the side of the tail entry before the coal bursts occurred. The value rapidly decreased from 0.97 to 0.61 within 3 days. Moreover, the value at the side of the head entry also declined from 0.39 to 0.32. It revealed that lack of shock $b$ value exhibited significant precursory information for predicting coal bursts occurring in flat seams whilst it exerted a poor prediction effect on the SICSs.

4.4.3. Microseismic Activity. Figure 8(a) shows the change curve of MS activity in the 5521-20 panel. Similar to the $b$ value and the total fault area, the global change trend of MS activity within the $R_f$ was similar to that of $R_r$. Prior to June 24, the MS activity at the roof side was generally stable, and its value was not significantly changed. However, after June 24, the value of MS activity in the $R_f$ sharply rose to a peak (0.402) when the coal bursts appeared on June 29. In contrast, the value in $R_r$ decreased, so that the difference of the value between the roof and the floor sides gradually increased. After this, the value of the MS activity started to decrease, which also indicated that the MS activity was dramatic in the roof side before the coal bursts and so the risk degree of dynamic-load source increased. The MS activity of the coal-rock mass in the floor side was stable. As a result, the MS activity in the roadway zones at the roof and the floor sides was also inconsistent; therefore, the MS activity can be taken as an index reflecting precursory information for coal bursts.

Figure 8(b) illustrates the change curve of MS activity in the 3102 panel. Overall, the tail entry and the head entry exhibited a similar trend of MS activity. The value of MS activity constantly grew before the coal bursts happened. These observations implied that the risk degree of dynamic-load source in this stage constantly increased, showing obvious precursory information. The risk degrees of tail entry and head entry in the LW3102 panel were consistent, which was significantly different from the contradiction shown in the risk degree of the $R_f$ and $R_r$ in the LW5521-20 panel.

4.4.4. Total Stress Equivalent. Figure 9(a) shows the change curve of total stress equivalent in the 5521-20 panel. Before the coal bursts, the total stress equivalents within $R_f$ and $R_r$ were steadily changed within the range of $<$300. From June 28, the total stress equivalent at the roof side sharply grew and instantaneously increased from 267 to 534 when the coal bursts occurred on June 29. In the subsequent four days, the total stress equivalent was generally still larger than 500 even though it declined. After this, the value sharply decreased to 222. As an important index for monitoring the activity of roofs [15], the sensitivity of the total stress equivalent interpreted that the coal bursts occurring in $R_f$ of the LW5521-20 panel were induced by dramatic activity of hard roofs. Therefore, the total stress equivalent can be taken as important precursory information and a warning index.

Figure 9(b) illustrates the change trend of the total stress equivalent in the 3102 panel. Similar to the other indices, changes in the total stress equivalents at the tail entry and the head entry were also significantly consistent. Before coal bursts, the total stress equivalent of the tail entry suddenly increased from 280 to 3200, showing a favorable effect of warning.

In the above sections, temporal distribution curves of the four MS monitoring and warning indices before and after coal bursts were analyzed. In the SICSs, $b$ value, MS activity, and total stress equivalent all exhibited obvious anomalies before a coal burst occurred, showing explicit precursory information and high index sensitivity. The three indices can be used for warning and predicting coal bursts in the SICSs. However, a lack of shock $b$ value with low index sensitivity did not show any corresponding precursory information. Thus, the index was not applied as a monitoring and warning index. The above four indices all delivered a favorable effect of warning on the flat seams. In the change curves of the indices for the SICSs, the values of the indices of $R_f$ were all larger than those of $R_r$. Moreover, differences between the values of the indices at the roof and the floor sides gradually increased before a coal burst occurred, showing significant inconsistency. The data indicated that the activity of the coal-rock mass of the $R_f$ was more dramatic, which was favorably coupled with the theoretical analysis results: $R_f$ was more greatly influenced by dynamic loads of roofs. In the flat seams, the changes of indices at the two roadways were consistent. Therefore, the monitoring and warning in SICSs was different from that in the flat seams where the index—lack of shock $b$ value exhibited a poor effect of warning whilst the other three indices exerted a favorable prediction effect. Moreover, the constantly rising risk degree of the $R_f$ reflected by indices and the contradiction of indices at the roof and the floor sides can be used as precursory information for warning.

4.4.5. Seismic Tomography. Figure 10 displays the seismic tomography results in the 5521-20 panel from June 4 to July 14, 2016. It shows the distribution of seismic wave velocity in a profile of the panel. In the figure, the value of An reached 0.71, being at a strong risk degree corresponding to coal burst. In contrast, the coal-rock mass of $R_r$ nearly did not show an abnormal wave velocity.

By comparing the seismic tomography results and the distribution curves of static stress obtained through theoretical calculation, it can be found that in the propagation process of stress along the strike of the panel from the roof side to the floor side, An value gradually decreased from 0.5, then 0.3 to 0.1. The static stress gradually decreased in the transfer process from the roof side to the floor side. The results of the stress nephogram were favorably coupled with that of the stress distribution curve. Thus, the seismic tomography result was considered as a warning index for monitoring static stresses.
Figure 11 shows the seismic tomography result of seismic waves in the 11-3102 panel from February 1 to March 5, 2018. In the mining stage, the static stresses on the tail entry and coal pillar were high and An value reached 0.42, which was at a risk degree corresponding to a strong coal burst. In addition, an MS event with high energy ($1.0 \times 10^7$ J) occurred in the vicinity of the zone subjected to a coal burst and the superposed load of high static stress and strong dynamic stress led to the coal burst.

By comparing the seismic tomography result of the 3102 panel with that of the 5521-20 panel, it can be seen that zones subjected to coal bursts are those with a high An value. This indicated a high risk degree, and MS events with high energy appeared around the position where the coal bursts occurred. However, there were also differences between the SICSs and the flat seams. At first, in terms of range of the high-stress zone; high-stress zone in SICSs was mainly found in $R_r$, and the scope with $116 \times 202$ m all exhibited high stress. In other areas, static stress was low.

As shown in Figure 11, there was a wider distribution range of high-stress zone in flat seams: a high-stress area with $325 \times 360$ m was found within the panel. Within the adjacent 3103 panel, there was also a high-stress zone of $570 \times 138$ m. Secondly, in terms of the risk degree, the degree of stress concentration in SICSs was higher and An value was up to 0.71 at most. However, the maximum An value in nearly all horizontal coal seams was only 0.42. In the SICSs, the region of high stress concentration was smaller, which was only found in the $R_r$. In contrast, in the flat seams, the region of high stress concentration was more widely distributed and multiple regions of stress concentration were found. Therefore, the degree of stress concentration in the
SICSs was higher than in the flat seams; therefore, the risk of coal burst in the SICSs was higher.

5. Conclusion

(1) The stress distribution curve showed that static stress (27~44 MPa) on coal mass in \( R_r \) was significantly greater than that (10~10.45 MPa) of \( R_f \) and the dynamic load induced by the fracturing of thick and hard roofs decreased with increasing propagation distance. The dynamic load was superposed with static stress during propagation in the roadways. The dynamic and static stresses on the roof side were both larger than those on the floor side.

(2) The monitoring and warning indices for SICSs and flat seams were compared. The \( b \) value was obtained, and MS activity and total stress equivalent showed a significant anomaly peak before the coal bursts occurred in SICSs. Before the coal bursts occurred, the anomaly continuously appeared for more than 3 days. The overall change trends of warning indices of \( R_r \) and \( R_f \) were similar. The lack of shock index did not exhibit obvious precursory information indicating the anomaly. In the flat seams, all the four indices showed significant precursory information, thus having a favorable warning effect.

(3) Before a coal burst happened, the difference of indices in \( R_r \) and \( R_f \) in SICSs gradually increased, showing a contradictory effect between the roof and the floor sides. It also revealed that the activity of the coal-rock mass on the roof side was more dramatic in generating strong dynamic loads. The tail entry and the head entry in the flat seams exhibited obvious consistency. The change trends of the indices at the tail entry and the head entry were similar. Therefore, continuity and contradiction can be used as precursory information for judging the coal burst risk of SICSs.

(4) The static stress based on seismic tomography results in SICSs was favorably coupled with the theoretical...
analysis result, in which the An value was 0.71 at most. In the propagation process from the roof side to the floor side, the An value gradually decreased from 0.5, then 0.3 to 0.1. It indicated that the static stress gradually declined from the roof side to the floor side. By conducting a comparison with flat seams, it can be found that the area of high stress concentration in SICs was smaller while the degree of stress concentration was higher.

Data Availability
The in situ measurement data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest
The authors declare that there are no conflicts of interest regarding the publication of this paper.

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