Mechanism and Prevention of Rockburst in Deep Multipillar Gob-Side Entry

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Rockburst frequently occurs in deep multipillar gob-side entry in Inner Mongolia and Shaanxi, China. A case study of the Hongqinghe coal mine was analyzed to reveal the occurrence mechanism of rockburst in deep multipillar gob-side entry through theoretical and applied research. And new control methods were put forward. The results show that there is an essential difference between the surrounding rock load characteristics of multipillar gob-side entry and single-pillar gob-side entry. Within the influence area of the lateral goaf, more coal pillars will promote stress concentration, and the high stress concentration area will migrate to the coal pillar of mining roadway. The hanging roof of the working face can cause the stress concentration in the area of leading coal pillar to reach 5 times. The multipillar gob-side entry is less affected by the dynamic load of the roof of the lateral goaf. The ‘F-shaped and L-shaped’ stress source structure model of the deep gob-side multipillar entry was established, and the occurrence mechanism of rockburst is revealed. On the one hand, the static load of rockburst start foundation is formed under the superposition of lateral goaf, rear goaf, and multicoal pillar. On the other hand, the superposition of the foundation static load and the opportune static load induces the start of rockburst. Aiming at the two types of load sources, the fracturing method of kilometer bedding drilling in the roof of coal pillar area is proposed to reduce the foundation static load. The treatment method of periodic tendency blasting fracture of leading roadway roof in a working face reduces opportune static load. The field test has been carried out, and the effect was good.

1. Introduction

In China, about 70% of rockburst in coal mines occurs in gob-side entry [1–4]. Case statistics of rockburst in gob-side entry is shown in Table 1 [5–8]. Many scholars have carried out studies in the prevention theory and technology of rockburst in gob-side entry [9–14]. For instance, taking the coal body in the high stress difference area as the research object, Jiang et al. analyzed the stress conditions, stress gradient conditions, and burst tendency conditions of coal body in the gob-side entry and deduced the engineering criterion of rockburst risk [15]. Tan et al. proposed the ‘stress relief-support reinforcement’ synergetic control theory, including the support reinforcement of shallow fractured zone of coal rib and the stress relief of deep intact zone of coal rib, roof, or floor [16]. Cheng et al. and Wang et al. realized the prevention and control of roadway rockburst by adjusting the horizon of gob-side entries [17, 18]. Pan et al. studied the causes and prevention of rock burst in deep gob-side entry of two soft coal seams [19]. From the point of view of stress control and support design, Li et al. put forward the prevention and control principle of the driving roadway along the goaf in the burst tendency coal seam on the basis of analyzing the rockburst inducing factors and deformation characteristics of the roadway [20]. Li et al. reduced the static load of coal and rock mass around the gob-side entry by optimizing the layout of the gob-side entry, dissipated the dynamic load transmitted to the roadway, and controlled the stress of entry surrounding rock below the critical stress level [21]. In terms of prevention and control technology, hydraulic fracturing and top cutting pressure relief methods have been widely carried
out \cite{22-24}. The above studies basically focus on the traditional single coal pillar gob-side entry and rarely involve the mechanism and prevention of rockburst in multipillar gob-side entry.

In Hujite mining area and Nalinhe mining area in Inner Mongolia, China, due to simple mine conditions, large mine output, and difficult connection of the working face, the mining face of the mine generally adopts double roadway excavation, in which the outer roadway serves the next connecting mining face. Similarly, double roadway excavation is also widely used in the Binchang mining area of Shaanxi Province, China, in which the outer roadway is used as the special draining roadway of the working face. However, as the coal pillar with a width of almost 30 m must be reserved for double roadway excavation, with the increase of mining depth, the above outer roadway will be seriously damaged by primary mining, and it is difficult to use for the next working face, so the coal pillar must be reserved again to excavate the roadway. Even so, in the mining process of the working face, the rockburst in the forepoling range of the newly excavated roadway continues to appear, and unreasonable roadway layout has been formed. At present, it is urgent to solve the problem of frequent rock burst under such conditions and realize safe mining in the working face. Due to the unclear surrounding rock load characteristics and rockburst mechanical model of this kind of multicoal pillar gob-side entry, the continuation of the previous prevention and control method of cutting off the hanging roof of the lateral goaf in the single-pillar gob-side entry has not prevented the continuous occurrence of rockburst.

In this work, a case study of Hongqinghe coal mine in Inner Mongolia, China, was analyzed to reveal the essential difference between the surrounding rock load characteristics of deep multipillar gob-side entry and single-pillar gob-side entry. The mechanism of rockburst in multipillar gob-side entry is studied by establishing the structural model of bearing 'F-shaped and L-shaped' stress resource. Based on the research finding, a new prevention method has good application effect in field engineering and provides theoretical guidance for the prevention and control of rockburst in similar mines.

### Table 1: Case statistics of rockburst in gob-side entry.

<table>
<thead>
<tr>
<th>Date of occurrence</th>
<th>Occurrence location</th>
</tr>
</thead>
<tbody>
<tr>
<td>2020.10.8</td>
<td>Kuangou coal mine, Xinjiang Province, China</td>
</tr>
<tr>
<td>2016.7.22</td>
<td>Dongbaowei coal mine, Heilongjiang Province, China</td>
</tr>
<tr>
<td>2016.9.25</td>
<td>Junde coal mine, Heilongjiang Province, China</td>
</tr>
<tr>
<td>2018.11.11</td>
<td>Hongyang No. 3 coal mine, Liaoning Province, China</td>
</tr>
<tr>
<td>2020.2.22</td>
<td>Rockburst in Xinjulong coal mine, Shandong Province, China</td>
</tr>
</tbody>
</table>

### 2. Engineering Background

Hongqinghe coal mine primarily exploits the No. 3\(^1\) coal seams, with an average thickness of 6.23 m and inclination angles of 1°-3°. The depth of the overburden was around 730 m. The direct roof of the coal seam is 10.3-25.97 m sandy mudstone siltstone, and the basic roof is medium grained sandstone with an average thickness of 58.37 m. The coal seam floor is sandy mudstone with an average thickness of 7.87 m, and there are multilayers of thick sandstone within 100 m above the coal seam. The coal seam has a strong burst tendency, while the floor and roof have a weak burst tendency.

Comprehensive mechanized coal mining method with great mining height is adopted in the mine. The 101 longwall panel, as the first mining panel of the mine, was completed in February 2018. The 103 longwall panel was the next mining panel of the mine. It was approximately 2480 m long and 210 m wide. The 101 panel adopts double tunneling, that is, the 101 tailgate was excavated together with the 103 main gate, leaving a 30 m wide coal pillar between them. The 103 main gate was deformed greatly during the mining process of 101 panel, which was difficult to use. So, a new 103 main gate was excavated at a distance of 30 m from the original 103 main gate later (see Figure 1(a)).

During the 103 longwall panel mining, multiprockburst occurred within 350 m of the leading face of the new 103 main gate. The ‘2018.11.30’ rockburst is analyzed as a typical case. The floor heave and two ribs convergence occurred within 350 m of the new main gate length, of which the area was a length of 243 m outside the forepoling (location and damage phenomenon of rockburst are depicted in Figures 1(a) and 1(b), respectively). Due to the high risk of rockburst and unclear prevention principle, the 103 panel is in halted state. In order to explore the mechanism and prevention methods of rockburst, this paper takes this as the background to carry out theoretical and experimental research.

### 3. Mechanism of Rockburst in Multipillar Gob-Side Entry

#### 3.1. Static Load Analysis of Surrounding Rock

##### 3.1.1. Inclined Static Load Analysis of Roadway

In order to obtain the stress distribution law under mining condition of multipillar gob-side entry of 103 panel, the finite difference method code FLAC\textsuperscript{3D} was selected for the numerical study. A numerical model was constructed based on the geological and engineering conditions of the 103 longwall panel. The model was 450 m wide, 500 m long, and 172 m high and simulated the transversal section of the longwall panel, see Figure 2. The boundary and bottom of the model move in a fixed normal direction. A vertical stress of 14.29 MPa was applied to the top boundary of the model to compensate the overburden stresses. And the Mohr-Coulomb constitutive model was adopted for the model. The main physical and mechanical parameters used in the model are from the Measurement report on physical and mechanical parameters and burst tendency of coal and rock, listed in Table 2.

Figure 3 illustrates the stress distribution under mining of multicoal pillar layout along goaf in 103 panel. It is clear that 103 main gate is affected by the goaf of 101 and 103, and both coal pillars suffered extremely high abutment...
stresses, especially the two ribs of the new 103 main gate (the maximum stress reaches 40 MPa and the stress concentration factor reaches 2). No distinct stress concentration within both sides of 103 tailgate, however, were observed.

In order to study the stress distribution law of the mining surrounding rock after adding the roadway and coal pillar, during numerical study, the stress distribution characteristics of another roadway excavated 30 m and 36 m away from the new 103 main gate are analyzed, respectively. The stress nephogram of the newly excavated roadway with 30 m and 36 m wide pillar are shown in Figures 4(a) and 4(b), respectively, and notable stress concentration within the pillar can be shown in both figures. Figure 4 shows that the stress distribution law of each scheme is generally similar, but the difference in the corresponding curve of different roadway excavation methods jointly indicates a fact: with the increase of the number of roadways, the stress of the both sides of the new 103 main gate is more concentrated (greater than 45 MPa). In other words, the regional static load is highly concentrated, which is affected by the superposition of 101 goaf and 103 goaf, and the stress concentration will further aggravated by excavating within this area.

3.1.2. Strike Static Load Analysis of Roadway. Figure 5 records the coal stress changes with 103 face advances monitored at the two monitoring stations within the forepoling range of the new 103 main gate. The stresses monitored by 31# and 33# monitoring stations illustrate that with 103 face...
approaching, the stress on both ribs continues to rise (the stress concentration factor greater than 5), which truly reflects that the roof above goaf cannot caving in time. As a result, with longwall face mining, the stress in the leading coal pillar area caused by large area hanging roof increases constantly, creating conditions of static load accumulation for the occurrence of 2018.11.30 rockburst.

3.2. Dynamic Load Analysis of Surrounding Rock. The position of microseismic events within the mining disturbance...
range of 103 face five days before the occurrence of ‘2018.11.30’ rockburst are displayed in Figure 6. The microseismic events were mainly concentrated in the 103 goaf, leading longwall face, and coal pillars between multiroadways. Events with $10^3$ energy level were sporadically distributed in 103 goaf, while events with $10^4$ energy level were mainly concentrated in the influence area of the abutment stress of 103 face. It can be inferred that the rear hanging of 103 goaf roof and the lateral hanging roof of 101 goaf on the coal pillars, resulting in surrounding rock fracture and micro-seismic cluster events. With the further increase of the hanging roof length, the influence range of the abutment stress extends constantly. On November 30, a rockburst occurred in a coal pillar area 102 m away from working face in the new 103 main gate, while the 101 tailgate 102 m away from the goaf of 103 face is intact. It is demonstrated that this rockburst was not induced by dynamic load of roof breaking in goaf.

3.3. Mechanism of Rockburst. According to the regional characteristics of rock burst in Hongqinghe coal mine, the engineering structure model of the intersection area between the gob-side entry and working face as shown in Figure 7 has been built. With the formation of lateral goaf and rear goaf, the overlying roof of the coal seam forms an ‘F-shaped’ cantilever structure, and the cantilever beam gradually lengthened from bottom to top causes the stress concentration of the bearing coal under it. When the gob-side entry has not been excavated, the stress concentration of the lateral coal body and the leading working face are shown in Figures 8 and 9, respectively. When multiroadways have been excavated in the wide coal pillars, the stress distribution law shown in Figure 10 can be obtained by referring to Figure 3. The roadways have been excavated in the wide coal pillar in the stress concentration area, resulting in the stress concentration on both ribs (see Figure 10). After excavating the new 103 main gate, the stress is closer to the critical state. The whole leading pillar and the face end form an ‘L-shaped’ stress concentration area (see Figure 11). Different from the layout of a single gob-side entry, the static load concentration area is far away from the lateral goaf and transferred to the side of coal mining, mainly concentrated on the two ribs of the new 103 main gate.

Combined with Figure 10, it is analyzed that the stress of the left rib of the new 103 main gate is closer to the critical stress, and this area is taken as the research object.
According to the research of Arvishen [26], the static load of the left rib is divided into three parts: volume strain energy $U_v$, deformation energy $U_f$, and roof bending energy $U_w$:

$$ U_{ST} = U_v + U_f + U_w. \quad (1) $$

The elastic energy accumulated by the coal in the left rib of the new 103 main gate due to the volume compression of the overlying strata is approximately calculated as

$$ U_v = \frac{(1 - 2\mu)(1 + \mu)^2}{6E(1 - \mu)^2} \gamma^2 H^2. \quad (2) $$

In the formula, $\mu$ is Poisson’s ratio of coal and rock mass in this area; $r$ is the unit weight of coal and rock mass, N·m$^{-3}$; $H$ is the mining depth, m; and $E$ is the modulus of elasticity, GPa.

The elastic energy accumulated by the coal in the left rib of the new 103 main gate due to the dilatation is approximately calculated as

$$ U_f = \frac{(1 + \mu)(1 - 2\mu)^2}{3E(1 - \mu)^2} \gamma^2 H^2. \quad (3) $$

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Figure 7: ‘F-shaped and L-shaped’ force source structure of multi pillar gob-side entry and stope [2].

Figure 8: Lateral roof structure of longwall face before roadway excavation [2].

Figure 9: Distribution of advance abutment stress in working face [2].
The roof bending energy is divided into the cantilever energy of the lateral goaf and the rear goaf of 103 face and is approximately calculated as

\[ U_w = U_{w1} + U_{w2}, \]  
\[ U_{w1} = \sum_{i=1}^{n} \frac{q^2L_i^5}{8EJ}, \]  
\[ U_{w2} = \sum_{i=1}^{n} \frac{q^2L_i^5}{8EJ}. \]

In the formula, \( q \) is the unit length load of cantilever of overburden, \( \text{N/m} \); \( L \) is the cantilever length of the hanging roof, \( \text{m} \); and \( J \) is the moment of inertia of the hanging roof, \( \text{m}^4 \).

Therefore, according to the energy condition of rockburst start [27, 28], the equation of rockburst occurrence in the rib of the new 103 main gate is \( U_{ST} > U_c \), that is,

\[ \frac{(1 - 2\mu)(1 + \mu)^2}{6E(1 - \mu)^2} \gamma^2H^2 + \frac{(1 + \mu)(1 - 2\mu)^2}{3E(1 - \mu)^2} \gamma^2H^2 + \sum_{i=1}^{n} \frac{q^2L_i^5}{8EJ} \]

\[ + \sum_{i=1}^{n} \frac{q^2L_i^5}{8EJ} > \sigma_c^2 \frac{2E}{2E}. \]

In the formula, \( \sigma_c \) is the uniaxial compressive strength of coal, and \( U_c = \sigma_c^2 / 2E \) is the minimum energy required for dynamic instability when the microunit in the limit equilibrium zone of surrounding rock reaches the critical load.

According to the analysis of the load distribution characteristics of the surrounding rock of the new 103 main gate in Hongqinhe coal mine, the static load in the left rib has reached the critical state under the superposition of three factors: lateral goaf, rear goaf, and coal pillars. In other words, volume deformation energy \( U_v \), form deformation energy \( U_f \), and roof bending energy \( U_w \) in the conventional state promoted the regional load of the coal pillar to reach the critical state.

When the working face is square-shaped or the hanging roof with large area and long distance, it is obtained from formula (6) that the bending energy accumulated by the cantilever state of the hard hanging roof above the coal seam is directly proportional to the \( 10^5 \) of its cantilever length. At this time, the cantilever above the rear goaf of the working face increased \( \Delta L_c \), resulting in the increase of roof bending energy, which is the opportune static load. At this time, the total energy to induce rockburst start can be calculated by

\[ \frac{(1 - 2\mu)(1 + \mu)^2}{6E(1 - \mu)^2} \gamma^2H^2 + \frac{(1 + \mu)(1 - 2\mu)^2}{3E(1 - \mu)^2} \gamma^2H^2 + \sum_{i=1}^{n} \frac{q^2L_i^5}{8EJ} \]

\[ + \sum_{i=1}^{n} \frac{q^2(L_i + \Delta L_i)^5}{8EJ} > \sigma_c^2 \frac{2E}{2E}. \]

### 4. Prevention Methods of Rockburst in Roadway

According to the previous analysis, the excessive concentration of static load under the hanging roof of the lateral goaf, the rear goaf, and the layout of multicoal pillar, as well as the increase of roof cantilever length of goaf provide the opportune static load. The superposition of above two static loads leads to the rockburst of the new 103 main gate of the Hongqinhe coal mine. From the point of view of eliminating the conditions of rockburst start, on the one hand, the prevention and control of this rockburst need to reduce the static load concentration of the two ribs of the new 103 main gate, so as to reduce the static load concentration of the foundation. On the other hand, the cantilever length of the...
working face is reduced to eliminate the superposition of the opportune static load.

4.1. Reduction of Foundation Static Load. The static loads on the two ribs of the new main gate are concentrated, which is closely related to the hanging roof of lateral goaf. It is an effective method to cut off the hanging roof in the lateral goaf for the conventional layout conditions of a single coal pillar. However, for multicoal pillar roadway, because of the coal pillars with a total width of 60 m, the lateral hanging roof is mainly in higher position, and the breaking line of the roof is on the coal pillar of the original main gate. The roof cutting operation can only be implemented in the new main gate, and the roof breaking in the lateral goaf cannot be carried out. Therefore, this paper proposes to adopt the regional fracturing method of kilometer bedding drilling in the higher position roof to destroy its integrity and reduce the stress concentration in the coal pillar area as a whole. The maximum length of a single borehole can reach 1000 m, the maximum fracturing displacement is 1.5 m³/min, the maximum pressure is 70 MPa, and the fracturing radius is more than 50 m, which has a good weakening effect of the regional hard roof. The schematic diagram of the construction scheme is shown in Figure 12.

4.2. Reduction of Opportune Static Load. Reducing the cantilever length of the working face can not only prevent the abnormal increase of roof bending energy but also prevent the dynamic load caused by the collapse of large-area hanging roof. Therefore, it is proposed that roof blasting presplitting of the working face be carried out periodically along the inclined direction of the new main gate, so as to promote the periodic collapse of the hard and thick roof and avoid large-area hanging roof. The scheme of drilling position of the roof inclined broken roof blasting along the goaf roadway and regional pressure relief drilling of overlying roof strike of coal pillar group is shown in Figure 13.

5. Engineering Application

The 401111 longwall panel is the fifth working face in 401 panel, with a buried depth of around 720 m. The subhorizontal coal seam had an averaged thickness of 6.9 m, with strong burst tendency, while roof sandstone has weak burst tendency. The inclined length of the 401111 panel is 180 m, and 28 m and 40 m coal pillars are reserved in 401101 goaf to protect the water discharge roadway and the tailgate of 401111 panel. The roadway layout of the 401111 longwall panel is very similar to 103 longwall panel, and it is also arranged along the goaf with a multicoal pillar, resulting in multirockburst occurrence in the area affected by the front abutment stress of the tailgate during mining. The author believes that the rockburst occurrence in the tailgate has three induced factors: lateral goaf, rear goaf, and coal pillars. Under the superposition of three factors, the static load is concentrated, and the conditions of working face in square-shaped and the hanging roof with large area provides opportune load. In view of the frequent occurrence of rockburst in the working face, the prevention scheme mentioned above is proposed.
(1) The regional fracturing method of kilometer bedding drilling in roof (to regulate the static load)

As shown in Figure 14, the 1# long borehole is 70 m above the coal pillar, and the horizontal distance from the coal pillar of the tailgate is 15 m. The 2# long borehole is located above the solid coal, with a horizontal distance of 20 m from the stope rib of tailgate. Figure 15 shows the equipment of the regional fracturing of kilometer bedding drilling.

(2) Periodic roof blasting presplitting of the working face (to reduce cantilever length)

Starting from outside the leading influence area of the working face, roof inclined blasting presplitting boreholes are arranged in the tailgate and main gate of the 401111 longwall face, respectively. The roof treatment height is 30 m above the coal seam, and the vertical projection of most blast holes is 35.5 m, of which the vertical projection of charging section is 17 m and that of sealing section is 13 m. The blasting step distance in the leading area of both roadways is 10 m. Figure 16 shows the blasting presplitting scheme of the roof of the tailgate.

Figure 17 shows the distribution plan of microseismic events in the working face before and after the implementation of the scheme. It can be seen that the microseismic events in the working face can reach 230 m in front of the working face before the implementation of the pressure relief scheme. After the implementation, the microseismic events only reach 120 m in front of the working face, and the influence length is reduced by 48%. The regional fracturing in the roof has adjusted the stress concentration above the coal pillar in advance. After the influence of mining, the distribution of microseismic has shifted from the centralized distribution of the tailgate to the central part of the roof.
working face. The roof breaking by inclined roof blasting shortens the length of the hanging roof behind the goaf, the leading influence range is also relatively shortened, and the development length from microseismic events is shortened.

As shown in Figure 18, the presplitting hole of roof blasting in the tailgate shows water pouring, indicating that the fracturing in the higher position roof area and the roof breaking by lower blasting play a synergistic role.

Compared with before the implementation of the scheme, there was no frame pressing at the outlet of the working face, and the periodic weighting distance of the working face changed from 15.4 m before fracturing to 12.8 m after fracturing. The daily monitoring data of pulverized coal drilling cuttings on both ribs of the tailgate are normal, and there is no rockburst in the leading influence range of the tailgate. At present, the working face has been safely mined.

6. Conclusions

(1) The rockburst of traditional gob-side entry is mainly affected by the roof activity of lateral goaf, while the deep gob-side multipillar entry is mainly affected by multiroadway and rear goaf of this working face. The analysis of static load characteristics shows that within the influence range of lateral goaf, the increase in the number of coal pillars will increase the degree of stress concentration, and the high stress concentration area will migrate to the coal pillar of mining roadway. Before rockburst occurs, the coal pillar stress in the area ahead of the working face will reach 5 times. The analysis of dynamic load characteristics shows that the mining microseismic events mainly occur in the goaf and coal pillar area of the working face, and the multipillar roadway along the goaf is less affected by the dynamic load of the roof of the lateral goaf.

(2) The 'F-shaped and L-shaped' force source structure model of the deep multipillar gob-side entry was established. It is considered that the static load of rockburst start foundation is formed under the superposition of lateral goaf, rear goaf, and multicoal pillar. On the other hand, the increase of the cantilever length of the roof in the rear goaf provides the opportune static load, and the superposition of the foundation static load and the opportune static load induces the start of rockburst.

(3) From the point of view of eliminating the conditions of rockburst start, the prevention and control method of rockburst in deep multipillar gob-side entry were put forward. On the one hand, the regional fracturing method of kilometer bedding drilling in the higher position roof to destroy its integrity and reduce the stress concentration in the coal pillar area as a whole. On the other hand, roof blasting presplitting of the working face be carried out periodically along the inclined direction of the new main gate, so as to promote the periodic collapse of the hard and thick roof and avoid large-area hanging roof. The engineering application results show that the theory and method can achieve the purpose of preventing rockburst.

Data Availability

The data supporting the conclusion of the article are shown in the relevant figures and tables in the article.

Conflicts of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References


