Research Article

Mechanism and Energy Evolution Characteristics of Coal Burst in Mining Thick, Deep, and Large Inclined Coal Seams: A Case Study from a Chinese Coal Mine

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Coal burst is a severe and dynamic hazard, and understanding its mechanism is crucial in preventing such incidents. Strong tremors during the working face mining in the stress anomaly zone of the pinch-out coal seam are frequent. Theoretical analysis, numerical simulation, and field measurement methods are used to analyze the energy evolution law for mining at the working face and mechanism of coal burst. Mechanical models of the inclined and strike overhang structures are established, and the theoretical analysis of the strike and inclined energy distribution characteristics of the working face roof is carried out. The two key areas with a high overhang bending deformation energy accumulation are identified at the lower end and middle-upper part of the working face. The simulation results show that the energy accumulation area of the roof in the inclined coal seam has prominent asymmetric distribution characteristics. The roof energy accumulates in the lower end and middle-upper area of the working face. The floor energy accumulates in the lower end area of the working face, and the peak position of the overhead energy of the working face in the direction shifts toward the coal-wall side. Influenced by the local absence of the No. 8 coal seam, the vertical stress of the surrounding rock at the working face of the massive, inclined coal seam increased by 12.7%; the peak of roof energy at the working face inclination and strike increased by 46.2% and 32.2%; and the range of roof energy accumulation expanded. A deep directional hole blasting plan to prevent the phenomenon at the working face roof is developed, which effectively reduces the stress and energy level of the inclined hanging roof and avoids the occurrence of coal bursts in the abnormal stress area of the working face.

1. Introduction

Coal bursts, a dynamic geological hazard in underground coal mining, are characterized by the sudden and violent failure of coal and rock masses with a large energy release. They pose a serious threat to the production and safety of underground coal mining or surface buildings and, in some cases, may result in injury and loss of life [1, 2]. Many countries, such as China, Poland, Russia, and South Africa, have reported coal burst accidents. In China, coal bursts have occurred in more than 170 coal mines [3]. In recent years, with the increase in the depth and intensity of coal mining in China, mining conditions have deteriorated dramatically, and the frequency of coal burst accidents has shown a rising trend. For example, on October 20, 2018, a coal burst occurred during the dip entry excavation at a mining depth of over 1020 to 1070 m in the Longyun Coal Mine, a 174 m long dip entry was damaged, twenty-one workers were killed, and four workers were injured [4]. In a B1 coal seam with a large dip angle in a Chinese coal mine, a rock burst accident
occurred on July 2, resulting in serious deformation of +500 m horizontal B3 roadway, roof subsidence, and floor heave, and the amount of roadway side heave reached 500 mm [5]. A major coal burst accident occurred at 5521-20 working face in the No. 5 mining district of Yaojie Coal Mine. The magnitude of the accident was 2.4 on the Richter scale, and the ground felt strong [6]. On March 15, 2013, a coal burst disaster happened in the Junde Coal Mine due to the periodic caving of a hard gritstone stratum, twenty-one workers were injured, and four workers were killed [7]. In China, the occurrence of coal bursts has been one of the most serious problems in deep coal mining and has garnered much public attention. Despite decades of research, the mechanism of coal bursts remains incompletely understood.

Statistical analysis shows that all types of mines and coal seams have reported the occurrence of coal bursts, with geological formations ranging from simple to complex, coal seams ranging from thin to extra thick, and dip angles ranging from horizontal to sharply inclined [8, 9]. Researchers have reached an agreement that there are primarily two key factors that cause the coal burst phenomenon, namely, mining engineering conditions and geological conditions [10–12]. It is widely known that many geological conditions (such as thick and hard roof, pitchout of the coal seam, faults, coal thickness, folds, and mining depth) are caused by geodynamic movement, and their characteristics directly determine the conditions of occurrence of coal bursts or other dynamic disasters [13–16]. The energy evolution regulation of the roof during mining at the working face under different geological conditions has different characteristics [17, 18]. Preliminary statistics indicate that coal burst events occurring near geological structures account for nearly 70% of the total in China [19]. In recent years, many domestic and foreign scholars have carried out a considerable amount of research on the mechanism of coal bursts and the energy evolution characteristics of the working surface. They have achieved good results, including the development of the principle of static and dynamic load superimposing impulse [20], stress control theory [21], instability theory of shock disturbance response [22], stiffness theory [23, 24], and energy theory [25, 26]. However, most of the above coal burst theoretical research results consider horizontal, near horizontal, and gently inclined coal seams for the study, and relatively little research is conducted on the mechanism and prevention of coal bursts in large inclination or sharply inclined coal seams.

Steeply inclined coal seams have special characteristics due to their geological deposition structure that is prone to roof deformation, energy accumulation, and stress evolution with asymmetric characteristics during working face mining [27–29]. Most of the existing research results focus on roof stability and roof energy distribution during the mining of large inclination coal seams, while studies on the coal burst mechanism are relatively few [30–32]. The mining of such coal seams results in a different coal burst mechanism, and it is impossible to achieve targeted and effective prevention and control by applying the principles connected with horizontal and gently inclined seams. When the working face is mined, the stress and energy in the rock surrounding the working face are in a dynamic equilibrium state, and tectonic stress, roof breakage, or other factors are more likely to cause destabilization of the roadway surrounding rock damage, resulting in coal burst accidents.

The site chosen for this study is an underground longwall face (LW7313) in a Chinese coal mine, Jiangsu Province, China, where strong tremors and coal bursts are the main safety threats during coal mining; especially, the local absence of No. 8 coal seam causes stress anomalies in the vicinity of LW7313. When the working face is mined around stress anomalies, the frequency and energy of strong mine tremors increase significantly with the enhancement of the integrity of the roof. This work establishes the mechanical model of inclination and strike overhanging roof structure and studies the bending deformation energy distribution characteristics of the hanging roof structure; numerical simulation analyzes the energy distribution characteristics of the roof on the inclined and strike working face; studies the energy evolution law and the mechanism of coal burst in the mining of massive, inclined coal seam; and formulates a prevention and control plan for energy release by deep directional blasting off the roof. It provides a theoretical and practical basis for the prevention and control of coal bursts in areas of stress anomalies in the massive coal seam.

2. Site Characteristics

2.1. Longwall Details. The selected coalface, LW7313 in a Chinese coal mine, is in Xuzhou City, northwest of Jiangsu Province, China. The research object coal mine has a high coal burst risk and is a characteristic coal mine with coal burst hazards. Based on preliminary statistics, at least five disastrous coal bursts have occurred in this mine.

The research object is endowed with No. 7 and No. 8 coal seams, which have a simple endowment structure. As shown in Figure 1(a), the strike length and inclined length of LW7313 are 1270 and 230 m, respectively. The coal seam thickness of LW7313 is 3.20 to 7.00 m (5.13 m on average) with an inclination ranging from 26° to 34° (30° on average); the coal seam has a strong coal burst impact tendency, the mining depth is 650 to 800 m, and it is a massive beam with a large inclination. The south of LW7313 has a 60 to 150 m coal pillar with LW7332 goaf and a 6 m coal pillar with LW7311 goaf; the working face adopts the collapse method to manage the roof; two normal faults with a drop of 1.2 to 1.4 m are developed inside the working face, and No. 8 coal seam is missing in the local area below the working face.

The roof of the coal seam of LW7313 is mostly dominated by the sandstone layer and mudstone layer, and Pratt’s coefficient of the rock is 4.7–15.0 (Figure 1(b)). The coal seam is overlaid successively by sandy mudstone (average thickness of 4.7 m) that forms the immediate roof, medium sandstone (average thickness of 16.1 m) in the main roof, etc. and which are underlain successively by sandy mudstone (average thickness of 11.2 m), No. 8 coal seam (up to 3.50 m thick), etc. Meanwhile, the main roof and floor were all classified as having a weak coal
burst tendency through laboratory coal burst tendency identification.

In summary, LW7313 has several geological features such as large coal seam dip angle, large coal seam thickness, overlying multilayer thick, hard roof, and local No. 8 coal seam gap underneath.

2.2. Microseismic Manifestation Characteristics. According to the geological characteristics of LW7313, it is divided into two mining stages: stage I: the working face with 0~350 m area (mining time: January to June 2020), the coal seam in this area is endowed with two normal faults with a drop of 1.2 to 1.4 m; stage II: 350~480 m area of the working face (mining time: July
to September 2020), the coal seam roof integrity in this area is high, and there is no fault structure. No. 8 coal seam pinch outline is distributed in the stage I and stage II.

Microseismic monitoring in mines allows seismic event location and calculation of seismic energy, infers the mining stress state, and evaluates coal burst hazard [7]. A microseismic monitoring system called SOS, developed by the Central Mining Institute of Poland, was installed in research object coal mine, and the maximum locating errors are 20 m in the horizontal direction and 30 m in the vertical direction, respectively. The seismic monitoring network in September 2020 is shown in Figure 1.

Figure 2 shows the localization results of strong mining tremors (energy greater than $10^4$ J) based on data during the mining period from January to September 2020 at LW7313. Figure 2(a) shows relatively few strong mining tremors within stage I, which are mainly distributed along the faults. Strong mine tremors are frequent in stage II, dangerous mine tremors with an energy greater than $10^5$ J appear gradually, and the dangerous mine tremors are mainly distributed along the middle of the working face and at the No. 8 coal seam pinch outline. From Figure 2(b), the total frequency and energy of microseismic activity in stage I are low. The total frequency and energy of microseismic activity gradually showed an increasing trend with the mining of the working face to stage II and continued to be at a high level. From Figure 2(c), it can be seen that the total microseismic energy of the work face continued to increase during the stage II retrieval, and the growth rate of the total microseismic energy was 7.6% and 17.3% in August and September, respectively. The total microseismic frequency continued to decrease, and the reduction rate of the total microseismic frequency was 13.4% and 31.4% in August and September, respectively; LW7313 shows obvious "low frequency-high energy" phenomenon during the stage II area retrieval, and the impact hazard of the working face is enhanced at this time.

Based on the analysis of microseismic monitoring data, the mining scale of stage I mining face is small; and stage I is coupled with the development of faults in the middle of the working face, the roof’s integrity is damaged, and the ability to accumulate elastic energy is relatively weak. So, the overall microseismic energy level during mining is not large. In stage II, with the increase in the mining scale of the working face and the enhancement of the integrity of the roof, its ability to accumulate elastic energy increases, and the roof breaking induces a large amount of elastic energy to be released suddenly, leading to further increase in the frequency and energy level of strong mine tremors, and dangerous mine tremors in the central area of LW7313.

When the microseismic energy is more significant than $5 \times 10^4$ J, the probability of coal cannon, tremor, and slaggng at the working face increases. Microseismic data show that the energy level and frequency of strong mine tremors gradually increase with the enhancement of the overburden integrity of the working face, and the impact hazard is enhanced. Therefore, it is essential to study the energy evolution law of the coal seam with a large dip angle and the mechanism of coal burst to ensure safe mining of the working face.

3. Construction of Mechanical Model and Bending Deformation Energy Distribution Law for Overhanging Roof of Thick Coal Seam with Large Dip Angle

3.1. Model of Inclined Overhang Structure. Results of the studies show that when the inclination angle of the coal seam is large, the rock refuses to overburden collapse after working face slides and accumulates downward along the incline and gradually forms a small waste-filled area in the lower part of the working face [33]. The coal pillars in the upper roadway of the working face still have a specific bearing capacity, thus causing the asymmetric characteristics of the force on the sagging roof of the large, inclined coal seam. Considering the self-weight stress of the overlying rock layer and horizontal tectonic stress, the physical model of the inclined hanging roof structure is established [34] (see Figure 3).

In order to facilitate the analysis of the mechanical characteristics of the inclined overhanging roof structure, it is assumed that the coal pillars of the roadway above the working face are spring-supported. By Hooke’s law $F_i = k \Delta$, the spring constant $k$ is related to the degree of coal pillar compactness, $\Delta$ is the main roof displacement, dip angle is $\alpha$, the roof of the lower part of the working face with inclined length $S$ extends toward the coal seam and can therefore be considered as a solid fixed end. To calculate the roof support force $\sigma_y$ for the length $x_i$ of the plastic zone of the coal seam, the expressions for the stress within the plastic zone at the edge of the coal seam and the width of the plastic zone can be used, where $P_x$ is the lateral binding force of the coal wall [35]. The support force $\sigma_y(x)$ of the coal wall in the plastic zone on the top along the positive direction of the $y$-axis is given by

$$\sigma_y(x) = \left( \frac{c}{\tan \varphi} + \frac{P_x}{L} \right) e^{2 \tan \varphi (\lambda m)x} - \frac{c}{\tan \varphi} \left( 0 < x < S_L \right),$$

(1)

where $P_x/\lambda = ((c/\tan \varphi) + [\delta_{y,\text{max}}]/\lambda)e^{/(2\tan \varphi(\lambda m)} - c$, $m$ is the vertical height of the section coal pillar (m), $c$ is the cohesive force between coal and rock (MPa), $\lambda$ is lateral pressure coefficient, $\varphi$ is the friction angle of coal-rock layer ($^\circ$), $S_L$ is plastic zone width (m), and $[\delta_{y,\text{max}}]$ is the peak coal seam lateral bearing pressure (MPa). The peak value is about 1.25 $F_{y}(0)$ based on the simulation results [34].

The lower part of the working face area gangue filling is denser than the upward, and the upward filling is looser than the lower. For the convenience of calculation, the model is reasonably simplified, assuming that the load $F_L(x)$ formed by the gangue filling acting on the lower surface of the main roof is a linearly decreasing triangular load along the positive direction of the $x$-axis. Since the coal wall near the lower part
Figure 2: Distribution map of microseismic activity: (a) localization plan of microseismic events (energy $> 10^4$ J); (b) microseismic frequency and energy distribution map; (c) trend graph of microseismic data.
where $S_l$ is the width of the waste filling area (m) and $S$ is the inclined length of the working face (m).

The upper part of the main top is subjected to the joint action of the self-weight load $G$ of the overlying strata and the horizontal tectonic load $F_h$, which can be simplified to a trapezoidal load $F_d(x)$ along the inclined direction of the coal seam. According to the results of the ground stress study, $F_h = \lambda \rho g H$. Assuming that the width of the overlying strata layer along the strike direction is the unit length, the expression of the main roof upper part load $F_d(x)$ at any section is shown in the following equation:

$$F_d(x) = -\left(\rho g (\sin \alpha + \cos \alpha) \right) \times \left[H_0 + (L + S_l - x) \sin \alpha \right] \ (0 \leq x \leq (S + S_l)).$$

where $F_d(0)$ is the load on the overlying strata at the origin acting on the hanging roof, $\rho$ is the average density of the overlying strata (kg/m$^3$), $g$ is the acceleration of gravity (m/s$^2$), $\alpha$ is the working face inclination angle ($^\circ$), and $H_0$ is the burial depth of the working face boundary (m).

$$M(x) = \begin{cases} \frac{[4F_d(0) + 11F_d(x)]x}{40} - \frac{F_d(x)(x - x)}{2} - \frac{[4F_d(0) + 11F_d(x)]x}{6} - \frac{F_d(x)(x - x)}{2} & 0 \leq x \leq (S_1), \\ \frac{[4F_d(0) + 11F_d(x)]x}{40} - \frac{F_d(x)(x - x)}{2} - \frac{[4F_d(0) + 11F_d(x)]x}{6} - \frac{F_d(x)(x - x)}{2} & (S_1 < x < S_1 + S_l), \\ \frac{[4F_d(0) + 11F_d(x)]x}{40} - \frac{F_d(x)(x - x)}{2} - \frac{[4F_d(0) + 11F_d(x)]x}{6} - \frac{F_d(x)(x - x)}{2} & (S_1 + S_l < X \leq S), \end{cases}$$

Under the minor deformation condition, the bending moment is zero because the suspended overburden of the goaf acts as a load on the roof through the center of the circle. So, without considering the axial load, the mechanical model of the inclined hanging roof structure is obtained [34], as shown in Figure 4.

### 3.2 Establishment of Bending Deformation Energy Distribution Function for Inclined Roof

According to the principle of superposition of forces under small deformations [36], the mechanical model of the inclined overhang structure can be regarded as a simple sum of three mechanical models. That is, the linear load $F_d(x)$ of the main roof in the upper side OA section (Figure 5(a)) + triangular linear load $F_L(x)$ under the action of gangue-filled support in BC section at the lower end of the main roof (Figure 5(b)) + linear load $F_s(x)$ under the action of coal wall support in the plastic weakening zone of the OB section (Figure 5(c)).

According to the superstationary theory [36], the three mechanical models are one-time superstationary structures. By neglecting the excess support reactions $F_1$, $F_2$, and $F_3$, it can be reduced to the basic static system of “one end fixed, one end free.” Then, the unit load method and Mohr’s integral method may be used to solve the deformation coordination equation to get the magnitude of the support reaction force of the three mechanical models, and finally, the beam internal moment functions $M_{F_d}(x)$, $M_{F_L}(x)$, and $M_{F_s}(x)$ of the three mechanical models can be deduced.
According to the principle of superposition of forces, the bending moment function \( M(x) \) at any \( x \) of the inclined suspended structural beam is obtained as in the following equation [34].

Among them, \( Y_1 \), \( Y_2 \), and \( Y_3 \) are all close to 0 and are ignored here.

Since the overhanging roof strike length is much smaller than the tendency length, the shear deformation energy is generally small than the bending energy and is neglected here. Set

\[
U(x) = \begin{cases} 
\frac{1}{2EI} \left\{ (s-x) \left[ T - \frac{F_d(s)(s-x)}{2} \right] + q_1(S_L - x) + \frac{\sigma_y(S_L)(S_L - x)^2}{6} + \frac{\sigma_y(S_L)S_1(S_L - x)^3}{6} \right\}^2, & (0 \leq x \leq S_L) \\
\frac{1}{2EI} \left\{ (s-x) \left[ T - \frac{F_d(s)(s-x)}{2} \right] + \frac{\sigma_y(S_L)S_1(S_1 + S_L - x)^3}{6} \right\}^2, & (S_L \leq x \leq S_L + S_1) \\
\frac{1}{2EI} (s-x)^2 \left[ T - \frac{F_d(s)(s-x)}{2} \right]^2, & (S_L + S_1 < x \leq s). 
\end{cases}
\]

\[ (5) \]
Based on the test results of the LW7313 loose ring, take the roof.

3.3. Energy Distribution Characteristics of Inclined Hanging Roof. Based on the test results of the LW7313 loose ring, take the roof.

The energy of the working face roof in the inclined overhang structure shows an asymmetric distribution, with two peak energy areas. Under the action of asymmetric load, the maximum bending energy point of the inclined overhang structure is in the coal wall support area at the lower end of the working face, located at x = 0. The plastic zone at the lower end of the working face roadway is caused by the joint action of \( F_d(x) \), \( \sigma_y(x) \) thus putting the gathered large amount of elastic energy coal rock layer in a critical destabilization state. Once the coal-rock structure is unstable, it is easy to exceed the critical value of the system dynamic instability \( U_{\text{kin}} \), inducing a coal burst hazard [37].

The second energy peak zone is located about 150 m from the working face (at \( x \approx 3/5S \)), not at the roof’s geometric center. The reason is that the roof in this area is subject to \( F_d(x) \), \( F_s \) synergistic action, relative to the lower gangue-filled area of the working face; the roof in this area has ample space for movement after breaking and is more active. When the roof breaks, the bending deformation energy accumulated in this area is suddenly released in the form of kinetic energy, likely to cause strong mine tremors induced in the middle and upper part of the working face, thus increasing the coal burst hazard of the working face.

3.4. Energy Distribution Characteristics on the Strike of the Hard Roof. The finite element analysis of the load distribution above the overlying key stratum shows that, like the advanced bearing pressure on the coal seam, the roof in front of the coal wall is affected not only by the uniform load but also by the advanced bearing pressure [38]. The mechanical model of the mining field overlying rock is shown in Figure 7. The coal seam roof far ahead of the coal wall is in an elastic state, the coal seam roof near the coal wall is in ultimate equilibrium, the bearing pressure is greater than the uniform load far away, and the peak position of the advanced bearing pressure load is in front of the coal wall, and the distance from the coal wall is l. The roof load far from the peak stress tends to the uniform load \( q_1 \) and \( q_2 \), respectively.

Scholars simulated the relationship between the advanced bearing pressure load on the roof of Figure 7 as [39]

\[
T = \frac{(4F_d(0) + 11F_d(s))s/40 - ((4F_d(0) + 11F_d(s))s/6)}{(4F_d(0) + 11F_d(s))s/40}.
\]

According to the relation between the bending deformation energy and the bending moment, the expression of elastic energy at any point \( x \) on the inclined hanging roof structure Equation (5) can be obtained [34].

\[
\frac{EI}{2} = 2300 \rho.
\]

The energy of the working face roof in the inclined overhang structure is shown in Figure 6. The combination of these two curves can well simulate the support stress distribution load in front of the coal wall in Figure 7.
According to the research results [39], the bending strain energy density of the rocking beam in the x-section is

\[
\frac{dU}{dx} = \frac{M^2(x)}{2EI},
\]

(8)

where \(M(x)\) is the cantilever bending moment; \(E\) is the elastic coefficient of materials; and \(I\) is section moment of inertia.

Because the calculation of mantle rock energy density is the square of bending moment \(M(x)\) divided by the sizeable constant \(2EI\), based on Figure 9 and Equation (8), the energy distribution curve of LW7313 under theoretical calculation is drawn, as shown in Figure 10.

The area enclosed by the \(dU(x)/dx\) curve and the x baseline for any zones in Figure 10 is the bending strain energy stored in the roof of the hanging of that zone. The area of concentration is at 40 m before and after the coal wall to release strain energy from the sagging roof.

4. Simulation Analysis of Energy Distribution Characteristics in Anomalous Stress Region of Thick Coal Seam with Large Dip Angle

4.1. Model Establishment. To study the stress and energy distribution characteristics of the surrounding rock during mining in the working face of thick coal seam with large inclination angle under different geological characteristics, the FLAC3D model was established after appropriate simplification based on the geology and overburden conditions of the LW7313, model size: \(2670 \times 772 \times 534\) m (X \(\times\) Y \(\times\) Z). Horizontal displacement constraints are applied at both ends of the model, horizontal and vertical displacement constraints are applied at the model’s bottom, and uniform loads are applied at the top of the model to a simulated depth of 250 m.

There are two simulation scenarios: scheme (1) with No. 8 coal missing area and scheme (2) without No. 8 coal missing area. Based on the results of a geological survey of working face and determination of coal-rock mechanical parameters, the model coal-rock mechanical parameters are set after appropriate discounting, as summarized in Table 1. Combined with the assignment characteristics of LW7313, the adjacent working face was excavated in
sequence, and LW7313 was gradually excavated; the model is shown in Figure 11.

Figure 12 shows the characteristics of the stress distribution of coal rock in the inclined section 30 m ahead of the working face of the thick coal seam with a large inclination. As can be seen from the figure, the simulation results of schemes \( ① \) and \( ② \) both show that the working face is affected by the overbearing pressure and there is a high stress level overall, indicating that the partial loss of No. 8 coal does not affect the overbearing pressure evolution pattern during mining.

The simulation results show that the stress value in the advanced area of the working face in scheme \( ① \) is generally higher than that in scheme \( ② \), and the vertical stress increment in the advanced area is generally in the range of 7.5% to 12.7%, influenced by the partial loss of No. 8 coal seam. The vertical stress increment is the largest in the No. 8 coal seam pinch-out line, indicating the formation of a stress anomaly area at the coal-rock partition line influenced by the absence of No. 8 coal.

4.2. Energy Distribution Characteristics on the Working Face Tendency. The LW7313 is affected by the local lack of 8# coal seam, so it has special geological conditions. Stress anomalies are likely to occur near the coal-rock junction around the coal seam pinch-out line, thus affecting the stress evolution characteristics and the overburden energy evolution law when mining the working face. In the comparison of micro-seismic monitoring data during mining at LW 7313, the dangerous mine tremors (energy > \( 10^5 \)) in stage II show the characteristics of distribution along with the No. 8 coal pinch-out line, indicating that the local stress anomalies have a more obvious ability to influence the overlying rock activity.

Figure 13 shows the energy distribution characteristics of the coal-rock layer in the inclined section after excavation of the working face of the thick coal seam with a large inclination angle. From Figures 13(a) and 13(b), after mining the working face, the roof and floor layer energy shows asymmetric distribution characteristics. The roof energy accumulation zone is in the lower end and upper-middle area of the working face, and the floor energy accumulation zone is located in the lower end area of the working face. The simulation results show that the roof’s energy accumulation range and peak energy in simulation scheme \( ① \) are more extensive than that in scheme \( ② \). But the floor’s energy accumulation range and energy peak do not change much. It indicates that the local absence of No. 8 coal causes the formation of a stress anomaly area in the missing area of the coal seam, which results in an increase in the range and peak of energy accumulation in the roof.

From Figure 13(c), the lower end area of the working face is affected by the concentration of lateral bearing pressure of the working face mining, and the energy accumulation phenomenon occurs. When there is No. 8 coal seam deficiency in the working face, the peak energy of the roof is significantly higher than when there is no No. 8 coal seam deficiency. And the energy increment is about 46.2%; when there is No. 8 coal seam deficiency in the working face, the peak energy area of the roof of the working face is shifted from the middle and upper part to near the No. 8 coal pinch-out line, which is consistent with the location of the occurrence of dangerous mine tremors.

### Table 1: Main coal and rock mechanical parameters.

| Lithology            | Density (kg·m\(^{-3}\)) | Bulk modulus (GPa) | Shear modulus (GPa) | Internal friction angle (°) | Cohesion (MPa) | Tensile strength (MPa) |
|----------------------|--------------------------|--------------------|---------------------|----------------------------|----------------|------------------------|
| No. 7 coal           | 1350                     | 2.1                | 1.2                 | 30                         | 1.4            | 2.45                   |
| No. 8 coal           | 1380                     | 1.9                | 0.9                 | 29                         | 1.2            | 2.3                    |
| Mudstone             | 2550                     | 5.8                | 2.8                 | 31                         | 4.2            | 2.83                   |
| Sandy mudstone       | 2560                     | 6.3                | 2.9                 | 32                         | 5.4            | 3.35                   |
| Fine-grained sandstone | 2610                   | 11.2               | 6.0                 | 34                         | 7.1            | 10.4                   |
| Siltstone            | 2595                     | 7.1                | 3.5                 | 36                         | 8.2            | 5.04                   |
| Medium grained sandstone | 2655                | 10.2               | 5.3                 | 35                         | 8.2            | 8.15                   |
| Coarse-grained sandstone | 2640                | 8.1                | 4.2                 | 33                         | 9.3            | 6.84                   |

4.3. Energy Distribution Characteristics on the Working Face Strike. Figure 14 shows the energy distribution characteristics of the coal-rock layer in the strike section after excavating the working face of the thick coal seam with a large dip angle. From Figures 14(a) and 14(b), the
energy accumulation range and energy magnitude of the roof and floor layer of the working face in simulation scheme ① are larger than the results of scheme ②. It indicates that the local absence of No. 8 coal causes the formation of a stress anomaly area in the missing area of the coal seam, which results in an increase of the range and peak of energy accumulation in the roof.

Figure 14(c) shows the energy distribution curve of the roof in the direction of strike after mining the working face. When there is No. 8 coal seam deficiency in the working face, the peak roof energy is significantly higher than when there is no No. 8 coal deficiency. The increment of roof energy is approximately 32.2%, the peak overhead energy area in the working face is shifted from 50 m when there is...
no No.8 coal deficiency to 15 m, and the peak overhead position of the roof is reduced by about 70%. It shows that affected by the local No. 8 coal absence, the peak position of the overhead energy of the working face is closer to the coal wall position; when affected by the strong mine vibration, the working face area is more prone to the dynamic phenomena such as the spalling rib and coal burst.

In summary, the numerical simulation results show that the absence of the No. 8 coal seam in the local area is likely to form a stress anomaly area in the coal-rock junction area, further causing stress anomalies in the local area of the coal-rock seam at the working face. The local absence of No. 8 coal causes the roof energy accumulation range of LW7313 to increase, the energy peak is higher, and the location of
the overhead energy peak is closer to the coal wall. Strong mining tremors are more likely to be induced in the stress anomaly zone and energy accumulation zone during working face mining, increasing the risk of coal burst impact at the working face.

5. Mechanism of Coal Burst in Abnormal Stress Area of Thick Coal Seam with Large Dip Angle

5.1. Microseismic Energy Evolution Characteristics of LW7313. Based on the microseismic monitoring data during the mining period of LW7313, the distribution characteristics of microseismicity on the strike and tendency of the working face were counted by area, as shown in Figure 15.

As can be seen from the figure, microseismic events on the working face are distributed normally, and the microseismic events are primarily distributed in the range of approximately 60 m before and after the coal wall of the working face, and the microseismic energy within 20 m in front of the coal wall is more than the rest of the area. In the inclination direction of the working face, the distribution of microseismic events is characterized by a “rising-descending-rising” distribution, and the microseismic energy is mainly distributed around the midline of the working face the range of about 70 m. The theoretical analysis and numerical simulation results are consistent with the microseismic energy distribution characteristics during the recovery period of LW7313.

5.2. Mechanism of Coal Burst in Abnormal Stress Area of Thick Coal Seam with Large Dip Angle. Based on the analysis of the energy distribution characteristics of the roof of the inclined overhang structure, numerical simulation results, and field measurement data, the lower end and the middle-upper part of the inclined working face show energy accumulation, the energy of the roof shows the asymmetric distribution, and the maximum energy accumulation point is not in its geometric center. When the working face is affected by tectonic stresses such as missing coal seams, the peak of roof energy accumulation will increase significantly (46.2% improvement in simulation results), and the roof energy accumulation range is further expanded.

Therefore, the mechanism of coal burst in the stress anomaly area of the massive, thick coal seam can be elucidated as the working face roadway enclosure system being in a dynamic stable state of stress and energy under the influence of self-weight stress, tectonic stress, and oversupport pressure. At this time, a large quantity of bending deformation energy accumulated in the lower end of the
working face and the middle-upper regions is suddenly released due to the roof breaking, increasing stress, and energy of the roadway enclosure system. If the stress threshold value of dynamic instability of the roadway enclosure system is exceeded, coal burst is easily induced.

The effective release of bending deformation energy accumulated in the roof is the key to the prevention and control of coal burst in the stress anomaly area of thick coal seam with large dip angle; based on the distribution characteristics of the bending deformation energy of the roof, the targeted directional deep hole blasting energy release measures are carried out in the energy accumulation area. The roof directional energy release and impact reduction area can be divided into the roadway area (area ①) and working face area (area ②), as shown in Figure 16.

Roadway area (area ①): The area of the working face roof due to \( \sigma_y(x) \) and \( F_{si}(x) \) synergistic effect, plus the area by the side of the side of the gangue filling influence, region of accumulation of the roof bending deformation energy is not released with the roof break. So, the release of energy in this area can generally be recognized as 0 J. However, once a large-scale destabilization movement of the roof occurs in the area ①, it will quickly lead to the sudden destabilization and destruction of the coal and rock seam in the energy-critical state in this area and induce coal burst disaster.

Working face area (area ②): the roof deep hole blasting is generally in the middle-upper area of the working face, and the theoretical analysis results show that the suspended roof in this area is the first to break at \( x = 3/5S \). The deformation energy in this area is mainly converted into kinetic energy released during roof breaking. When the released energy is greater than the minimum energy for destabilization and destruction of coal-rock seams, it is easy to induce coal burst in the coal-rock seams in the rupture area. Therefore, the prevention and control concept of area ① is to pre-reduce the level of elastic energy stored in the roof in this area and thus reduce the kinetic energy generated when the roof breaks.

### 6. Prevention and Control of Coal Burst in Abnormal Stress Area of Large Dip Thick Coal Seam

#### 6.1. Prevention and Control Plan

Based on the mechanism of the occurrence of coal burst in the stress anomaly zone of the massive coal seam, the main reason for the destabilization of the large inclined thick coal seam is that the elastic energy released by the top plate breakage is larger than the minimum energy that the roadway enclosure system can resist. Therefore, the essential technique to prevent this impact pressure accident is to effectively reduce the elastic energy accumulated in the inclined overburden structure and reduce the dynamic load disturbance brought by the overburden breakage [40]. In addition, strengthening the support of the working face roadway system can effectively improve the ability of the surrounding rock to resist the dynamic impact load.

Combining with the mining technology and geological characteristics of LW7313, a deep hole blasting scheme for the roof combining predischarge pressure energy release and decompression pressure discharge energy dissipation is designed based on conventional large-diameter bored pressure discharge in the coal seam. Preloading pressure roof blasting holes 1#, 2#, 3#, and 4# are arranged in the back mining lane before working face mining to weaken the roof, destroy the integrity of the roof, and release or transfer the accumulated elastic energy of the roof in advance, to reduce the risk of coal burst at the working face. If strong mine tremors occur frequently and the number of dangerous mine tremors increases significantly during the working face, blasting pressure relief holes (5# and 6#) are implemented in the middle-upper part of the working face to release energy from the overlying rocks in time to dissipate the elastic energy in the roof quickly. The layout of the roof blast holes is shown in Figure 17, and the blast hole parameters are shown in Table 2.

#### 6.2. Prevention and Treatment Effect Test

##### 6.2.1. Analysis of Seismic Computerized Tomography Results

The computerized seismic tomography (seismic CT)
The inversion evaluation index can make a dynamic evaluation of the impact hazard of the working face [41–43]. The higher the P-wave velocity (VP) of the coal-rock layer of the working face, the larger the positive anomaly coefficient An of the wave velocity, indicating that the higher the stress level of the surrounding rock in the area, the more serious the risk of coal burst [44–46].

In abnormal stress areas of thick coal seams with large dip angles, coal burst risk is primarily dominated by static stress. Accordingly, an assessment criterion for coal burst risk in Table 3 is built. Velocity anomaly An is determined by

\[ A_n = \frac{V_p - V_{ap}}{V_{ap}}, \]

where \( V_p \) is P-wave velocity in a specific voxel and \( V_{ap} \) is the average velocity of the model. It should be noted that the zones with positive anomaly and negative anomaly are overstressed and pressure-relieved, respectively.

In the paper, microseismic wave forms in the working face area from September 20 to October 10, 2020 (before pressure relief), and from October 10 to October 30, 2020 (after pressure relief), were selected as seismic computerized tomography data, and wave velocity (VP) and positive anomaly coefficient of wave velocity (\( A_n \)) were used as indicators to evaluate the risk of coal burst at the working face. The results of the seismic CT are shown in Figure 18.

The results of the seismic CT show that the region of high stress before pressure relief is mainly distributed in the central and middle-lower areas of the working face, with a peak wave speed of approximately 6.08 km/s and a wave speed anomaly index (\( A_n \)) peak of approximately 0.50. The stress concentration in the surrounding rocks of the working face is high, and the risk of the impact coal burst is considerable. The peak wave velocity and peak wave velocity anomaly index decreased by 18.4% and 54%, respectively, after pressure relief, indicating that the stress concentration in the central and middle-lower part coal-rock seam of the working face was significantly reduced after decompression and decompression of the roof.

In addition, the seismic CT results show that there is still a certain degree of stress concentration area in the central and middle-lower part of the working face after pressure relief, indicating that the decompression of the roof can effectively induce the release of roof energy, reduce the stress level of the roof, and reduce the risk of coal burst. However, it cannot eliminate the elastic energy and stress accumulated in the roof and cannot eliminate coal burst risk.

### 6.2.2. Comparative Analysis of Microseismic Data

The frequency and energy of strong mining tremors increased significantly from mining at LW7313 to September 2020, and

**Figure 18:** Seismic CT detection results of high stress area in inclined thick coal seam: (a) characteristics of wave velocity distribution before decompression (2020.09.20-2020.10.10); (b) characteristics of wave velocity distribution after decompression (2020.10.10-2020.10.30); (c) distribution characteristics of wave speed anomaly index (\( A_n \)) before decompression; (d) distribution characteristics of wave speed anomaly index (\( A_n \)) after decompression.

**Figure 19:** Analysis chart of microseismic monitoring data.
the work face was blasted in October with multiple deep holes in the roof (blast holes 5# and 6#) to relieve the risk of coal burst. The author selected microseismic event data from September (before pressure relief), October (pressure relief period), November (after pressure relief), and December 2020 (mining in pressure relief area) to carry out the analysis, as shown in Figure 19.

The statistical results of microseismic data show that the total energy per meter and the total frequency of microseismic per meter are decreasing after the pressure relief, which indicates that the stress level of the surrounding rock at the working face has been effectively reduced after the pressure relief. The decrease in energy and frequency of microseismic per meter in October and December is much more significant than in November, indicating that the timely adoption of pressure relief has a noticeable effect on reducing the stress level of surrounding rocks and the pressure relief offered by roof relief blasting has certain timeliness, which is conducive to safe mining later on.

7. Conclusion

(1) Microseismic monitoring data show that with the enhancement of the integrity of the roof layer, the total frequency, and energy of microseismic activity are significantly increased, and the overall distribution of strong mining tremors shows the distribution characteristics along the middle of the working face and the coal seam tip extinction line.

(2) Based on the structural mechanics’ models of the inclined overhanging roof and the heading overhanging heading, the distribution characteristics of the bending deformation energy of the roof were solved. The energy of the inclined hanging roof was asymmetrically distributed, and the peak was in the lower end and the middle-upper area of the working face, while the energy of the hanging heading roof was concentrated in the range of 40 m pre and post the coal wall.

(3) The numerical simulation results show that the absence of the No. 8 coal seam in the local area is easy to form a stress anomaly area in the coal-rock junction area, resulting in the formation of a high-stress level region in the working face. The local absence of No. 8 coal seam causes the energy accumulation range of the working face roof and the energy peak to increase, and the location of the peak overhead energy is closer to the coal wall.

(4) Based on the characteristics of the tilted hanging roof’s energy distribution and the mechanism of coal burst in a thick coal seam with a large dip angle, the prevention and control scheme of elastic roof energy involves directional energy release and load reduction. Microseismic monitoring data show that the directional roof blasting and load reduction prevention scheme can effectively reduce the elastic energy and stress level in the critical areas of the working face, effectively cutting off the energy transfer path and reducing the risk of coal burst. This result has a guiding significance for preventing and controlling impact pressure at the working face under similar conditions.

Data Availability

The figures and tables used to support the findings of this study are included in the article.

Conflicts of Interest

The authors declare no conflict of interest.

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