Hindawi
Shock and Vibration
Volume 2021, Article ID 5584411, 7 pages
https://doi.org/10.1155/2021/5584411

Research Article

Analysis on Rock Burst Risks and Prevention of a 54 m-Wide Coal Pillar for Roadway Protection in a Fully Mechanized Top-Coal Caving Face

Zhihua Li [1,2,3], Ke Yang [1,2,3], Jianshuai Ji [1,2,3], Biao Jiao [4] and Xiaobing Tian [4]

[1] *Key Laboratory of Coal Mine Safety and Efficient Mining of Ministry of Education, Anhui University of Science and Technology, Huainan 232001, China*
[2] *Institute of Energy, Hefei Comprehensive National Science Center, Hefei 230031, China*
[3] *School of Mining Engineering, Anhui University of Science and Technology, Huainan 232001, China*
[4] *Shaanxi Binchang Hujiahe Mining Co.' Ltd.', Xianyang 713600, China*

Correspondence should be addressed to Zhihua Li; lizhihua81@126.com

Received 3 February 2021; Revised 11 March 2021; Accepted 8 April 2021; Published 19 April 2021

Academic Editor: Junfei Zhang

A case study based on the 401103 fully mechanized caving face in the Hujiahe Coal Mine was carried out in this research to analyze the rock burst risks in a 54 m-wide coal pillar for roadway protection. Influencing factors of rock burst risks on the working face were analyzed. Stress distribution characteristics on the working face of the wide coal pillar for roadway protection were discussed using FLAC3D numerical simulation software. Spatial distribution characteristics of historical impact events on the working face were also investigated using the microseismic monitoring method. Results show that mining depth, geological structure, outburst proneness of coal strata, roof strata structure, adjacent mining area, and mining influence of the current working face are the main influencing factors of rock burst on the working face. Owing to the collaborative effects of front abutment pressure of the working face and lateral abutment pressure in the goaf, the coal pillar is in the ultimate equilibrium state and microseismic events mainly concentrate in places surrounding the coal pillars. Hence, wide coal pillars become the regions with rock burst risks on the working face. The working face adopts some local prevention technologies, such as pressure relief through presplitting blasting in roof, pressure relief through large-diameter pores in coal seam, coal seam water injection, pressure relief through large-diameter pores at bottom corners, and pressure relief through blasting at bottom corners. Moreover, some regional prevention technologies were proposed for narrow coal pillar for roadway protection, including gob-side entry, layer mining, and fully mechanized top-coal caving face with premining top layer.

1. Introduction

Rock burst is a dynamic phenomenon that is produced by releasing deformation energies from the roadway or surrounding coal rocks, with characteristics of sudden, sharp, and great damages. It is one of the typical dynamic disasters in coal mining [1, 2]. Rock burst can be influenced by many factors. Among them, stress concentration on coal pillars is an important influencing factor. Currently, many mining areas such as Shenhua Coal Mine, China Coal Mine, and Datong Coal Mine prefer presetting 20–50 m-wide coal pillars to maintain the roadway. However, these coal pillars cannot be recovered and can cause great resource wastes. Sometimes, they even make the roadway within the area of coverage of intensive mining, further leading to strong rock pressure phenomena such as roof falling and side collapse [3]. Therefore, determining the reasonable width of coal pillars is of important significance.

Recently, Chinese scholars have reported fruitful studies on determining the reasonable width and stability of coal pillars in different widths. Zhang and He [4] determined that the reasonable width of coal pillars in the fully mechanized caving face of Wangjialing Coal Mine was 8 m via numerical analysis. Yue et al. [5] believed that the reasonable width of coal pillars in a fully mechanized caving face of a 15 m-ultrathick coal seam in Tashan Coal Mine was 6 m. Liu et al. [6] discussed the stress distribution and deformation characteristics of surrounding rocks in protection roadways with different widths of coal pillars through a numerical simulation. By combining theoretical computation, numerical analysis, and field engineering measurement, Feng et al. [7] determined that the optimal width of coal pillars on the working face with a deep well and large mining height was 8 m. By combining ultimate equilibrium theory, numerical analysis, and field practices, Zhang et al. [8] concluded a method to determine the reasonable width of narrow coal pillars for gob-side advancing. Zhang et al. [9] determined that the reasonable width of small coal pillars for gob-side advancing on the 8407 fully mechanized caving face of Yangquan Fifth Coal Mine was 10 m.

When there is strong burst proneness of coal rocks, the reasonable width of coal pillars varies significantly under the additive effects of mining stress and field stress [10]. Nowadays, many studies on rock burst risks and determination of reasonable width of coal pillars in coal seams with strong burst proneness have been reported in China. Wang et al. [11] used burst initiation theory combined with the space structure of overlying strata to investigate the space structural characteristics of overlying strata on the island working face as well as the distribution and variation laws of stress fields in mining surrounding rocks through a similarity simulation test. They further discussed the mechanism of rock burst occurrence of coal pillars in the section of island working face. Qin [12] determined the main influencing factors of dynamic appearance during gob-side advancing of the 21306 roadway in the Cuimu Coal Mine. Hou et al. [10] evaluated size reasonability in existing coal pillars by using a borehole stress meter and PASAT stress field CT scanning technology. Li et al. [13] conducted a statistical analysis on microseismic monitoring data in regions with coal pillars of varying widths. They discussed the variation law of rock burst parameters and analyzed the signs of strong rock bursts. Yang et al. [14] analyzed the stress evolution law of surrounding rock in gob-side entry with different dip angles by using FLAC3D. Feng and Wang [15] investigated the simultaneous recovery of upper remnant coal pillars while mining the ultraclose lower panel using longwall top-coal caving.

A 54 m-wide coal pillar for roadway protection was preset in an intake airway on the 401103 working face of Hujiahe Coal Mine. Few studies have been carried out on the reasonability widths of coal pillars. Therefore, influencing factors of rock burst risks of the intake airway were analyzed based on the geological conditions of the 401103 working face. Regions with rock burst risks on the working face were also determined through a numerical simulation. The location of historical rock burst events and seismic energies were determined through microseismic monitoring. The corresponding prevention technologies were proposed.

2. Conditions of the Working Face

The 401103 working face is the fourth working face of the 401 mining area in Huajiahe Coal Mine, China. The coal pillars are protected by the five roadways in the north. There are also the 401 mining area and boundary coal pillars of Xiaozhuang well field in the south, 401102 fully mechanized caving face in the west, and coal pillars for roadway protection in the 401 panel in the east. On the 401103 working face, the gob-side advancing roadway is the intake airway, where coal pillars have a width of 54 m. The ground elevation of the working face ranges from +920.6 m to +1070.7 m, while the elevation of the coal seam floor ranges from +340 m to +350 m. The strike length and proneness length are 1643 and 190 m, respectively. The 4 fourth coal bed pitch, thickness, and hardness are 0°–3°, 25.0–28.0 m, and 1.8–2.4, respectively. The 401103 working face adopts the long wall layered fully mechanized top-coal mining. The heights of the cutting coals and coal caving are 3.5 and 10.0 m, respectively.

3. Influencing Factors of Rock Burst Risks of the Working Face under Study

3.1. Mining Depth. Accumulative elastic energy in coal rocks increases with the increase of mining depth, which increases the possibility of rock burst event accordingly [16, 17]. The buried depth of coal seams on the 401103 working face is 730 m, which can significantly influence rock burst.

3.2. Geological Structure. Practices have proven that rock burst often occurs in geological structural regions, such as synclinal axis, and surrounding areas of faults [1]. A1 syncline and A3 anticline exist in the 401103 working face. When the working face advances to the synclinal axis, there is a high rock burst risk.

3.3. Outburst Proneness of Coal and Roof Strata. Outburst proneness is an inherent attribute of rock burst in coal seams and a prerequisite for the occurrence of rock burst [1]. The 4 coal of Hujiahe Coal Mine has coal seams with strong outburst proneness, and the 4 coal roof belongs to the rock strata with weak outburst proneness.

3.4. Roof Strata Structure. According to the full histogram on the 401103 working face, the main roof consists of sandstones that are 10.2–20.0 m in thickness. In the process of fracture or slippage of the hard roof, considerable elastic energies are released suddenly, which easily causes rock burst events.

3.5. Mining of Adjacent Working Face. Gob-side advancing is the intake airway of the 401103 working face and is next to the 401102 gob in the west. The roof of the intake airway of the 401103 working face close to the 401102 gob has a large hanging arch where abundant elastic energies accumulate. The overall vibration of the hanging arch will generate considerable energies that are very likely to cause rock burst when they are transmitted onto coal rocks in the intake airway of the 401103 working face.

3.6. Mining Influence of the Current Working Face. Working face mining forms front abutment pressures in front of the working face. Stress concentration is formed as a result of the collaborative effect of the lateral abutment pressure in the gob and the front abutment pressure in the working face. Rock burst events occur when such stress concentration exceeds the strength limit of coal rocks.

4. Microseismic Monitoring of Rock Burst on the Working Face

Microseismic monitoring technology is characteristic of large-scale real-time dynamic monitoring, and it can offer the spatial location, time, and energy of rock bursts [18, 19]. Rock burst events during mining of the 401103 working face in Hujiahe Coal Mine were monitored by using the microseismic monitoring system. Several rock burst events have occurred since the mining of the 401103 working face. There were eight rock burst events in May and June, 2018. The statistics of these eight rock burst events are shown in Table 1. A rock burst event occurred in the intake airway of the 401103 working face on the evening of June 17, 2018, resulting in the full-sectional heaving floor in the range of 80–100 m on the first advance of the intake airway. The heaving floor quantity reached 300–500 mm and the local laitance on the roof fell off. The recorded time of the microseismic monitoring system was 23:15, June 17, 2018. The seismic energy was 1.7×10^4 J and seismic source was at 67 m of the intake airway's advance face on the 401103 working face. In addition, the edges of gob were 60 m away from the west of the intake airway (Figure 1).

According to the statistical analysis on historical rock burst events during mining of the 401103 working face, seismic sources of rock burst are concentrated in areas close to the section coal pillars, while rock burst events occur in the intake airway. This is mainly because high static loads are formed in wide coal pillars owing to the influences of the lateral abutment pressure in the gob. Large-scale roof breakage occurs as a result of the mining disturbances of the 401103 working face, which provides relatively high dynamic loads of rock burst. Given the collaborative effects of dynamic loads and static loads, coal rocks become unstable and the rock burst events occur [20].

5. Numerical Simulation on Regions with Rock Burst Risks in the Working Face

Coal rocks break only when the stress exceeds the strength [1]. Therefore, stress concentration regions on the working face were analyzed through FLAC3D numerical simulation, which was able to determine regions with rock burst risks in the working face.

5.1. Construction of the Numerical Model and Excavation Steps. A FLAC3D numerical simulation model was constructed according to the geological conditions of the 401103 working face. The model dimension was 400 m (length) × 550 m (width) × 130 m (height). The whole model is composed of 500,544 units and 522,000 nodes. The model was solved through the Mohr–Coulomb criterion [21]. The structural reference of rock strata is in the histogram of the T9 borehole which is close to the return airway of the working face.

Before calculation, 15.44 MPa vertical stress was applied onto the upper boundary of the model according to the practical location of the model in the strata. Displacement boundary constraints were likewise provided on the sides and bottom of the 3D model.

Excavation was finished in three steps. First step, the 401102 gob was excavated after initial balancing of the model. Second step, the mining roadway of the 401103 working face was excavated to achieve operation balance. Third step, the 401103 working face was excavated to achieve operation balance.

5.2. Distribution Characteristics of Lateral Abutment Pressures at Two Mining Roadways after Excavation Roadways. The vertical stress contour in the return airway before mining of the 401103 working face is shown in Figure 2. Since the return airway is in entity coals, stress peaks (20.78 MPa) occur symmetrically in coals on two sides of the return airway, with a stress concentration coefficient of 1.16 (stress of the primary rock is 17.89 MPa). The vertical stress contour in the intake airway is shown in Figure 3. With the intake airway 54 m away from the 401102 gob, stress peaks occur asymmetrically in coals on two sides of the intake airway. The stress peak at the outer side is 32.66 MPa and the stress peak at the inner side is slightly lower, valuing 30.34 MPa. High stress concentrations are formed in the coal pillar. The stress peak and stress concentration coefficient reach 38.11 MPa and 2.13, respectively. Stresses in the coal pillars show two peaks. A large elastic zone is formed in the coal pillar and the wide coal pillar is kept stable.

5.3. Distribution Characteristics of Lateral Abutment Pressures at Two Mining Roadways during Mining. The vertical stress contour along coal seams during mining of the 401103 working face is shown in Figure 4. Influenced by mining of the working face, a front abutment pressure peak is formed at about 10 m in front of the coal wall of the working face. At this position, the abutment pressure peak formed in the coal pillar is relatively high. Hence, a contrast curve of lateral abutment pressures between premining and postmining of this position is plotted (Figure 5).

Figure 6 illustrates that a very high stress concentration is formed in the coal pillar due to the collaborative effects of front abutment pressure on the working face and the lateral abutment pressures in the mining area. Lateral abutment pressures of the coal pillar in the gob change slightly. The lateral abutment pressure peak in the intake airway of the working face is influenced significantly by the mining activity and the increase of the stress peak from 32.66 MPa to 52.96 MPa. Vertical stress distribution in the coal pillar changes from an asymmetric "double-peak" shape into "single-peak" shape, accompanied by a narrowing elastic zone in the coal pillar. The coal pillar is in the limit

Table 1: Statistic of rock burst events.

Time	Location of seismic source	Seismic energy/J	Position of occurrence	Coverage of damages (m)
12:46, May 12	137 m in front of the working face and 38 m to the entity coal side of the intake airway	5.0×10^4	112–162 m on the advance face of the intake airway	50
21:44, May 19	129.5 m in front of the working face and 89 m to the entity coal side of the intake airway	5.4×10^3	15–70 m on the advance face of the intake airway	55
02:34, May 28	162 m behind the working face and 60 m to the entity coal side of the intake airway	5.8×10^4	24.6–52.6 m on the advance face of intake airway	28
20:59, May 31	88 m in front of the working face and 15 m to the entity coal side of the intake airway	7.8×10^4	0–50 m on the advance face of the intake airway	50
12:27, June 1	22 m behind the working face and intake airway	5.8×10^4	33–68 m on the advance face of the intake airway	36
1:22, June 5	13 m in front of the working face and 54 m to the mining area of the transportation roadway	4.4×10^5	6–54 m on the advance face of the intake airway	48
10:10, June 13	90 m behind the working face and 265 m to the mining area of the intake airway	3.8×10^5	80–103 m on the advance face of the intake airway	23
23:15, June 17	67 m in front of the working face and 60 m to the mining area of the intake airway	1.7×10^4	80–100 m on the advance face of the intake airway	20

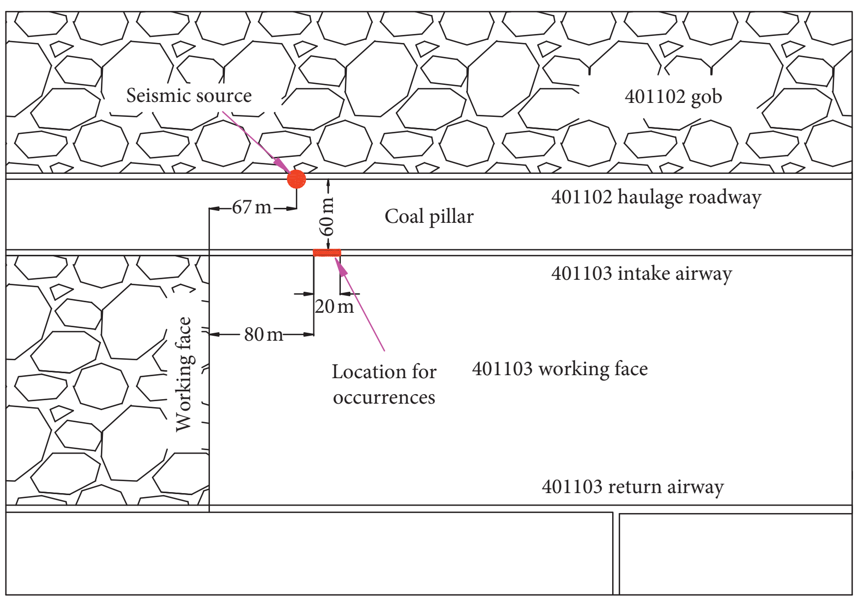

Figure 1: Location of seismic sources and occurrences of rock burst event at 23:15 pm on June 17, 2018.

equilibrium state. Abutment pressures in surrounding rocks on two sides of the intake airway increase quickly, indicating very high rock burst risks.

6. Prevention and Control of Rock Burst

6.1. Local Prevention Technologies. The numerical simulation and microseismic monitoring indicate that the intake airway of the 401103 working face has very high rock burst risks. Hence, some countermeasures are adopted in the intake airway to decrease the rock burst risks of the working face, such as pressure relief through presplitting blasting in roof, pressure relief through large-diameter pores in coal seam, coal seam water injection, pressure relief through large-diameter pores at bottom corners, and pressure relief through blasting at bottom corners.

6.1.1. Pressure Relief through Presplitting Blasting in Roof. In this countermeasure, three blasting holes are formed in one group. One blasting hole orients to the inner wall (solid coal) with an elevation angle of 65°, while the other two blasting holes point to the outer wall (coal pillar) with elevations of 65° and 50°, respectively. The diameter of each blasting hole is 75 mm. The sealing length, charging length, and charging load of blasting holes are 22 m, 18 m, and 50 kg, respectively.

The interval between groups is set to 5 m. The presplitting blasting hole layout in the roof is shown in Figure 6.

6.1.2. Pressure Relief through Large-Diameter Pores in Coal Seam. Large-diameter holes are constructed from the outer wall of the intake airway to the coal pillar. The holes are 1.5 m

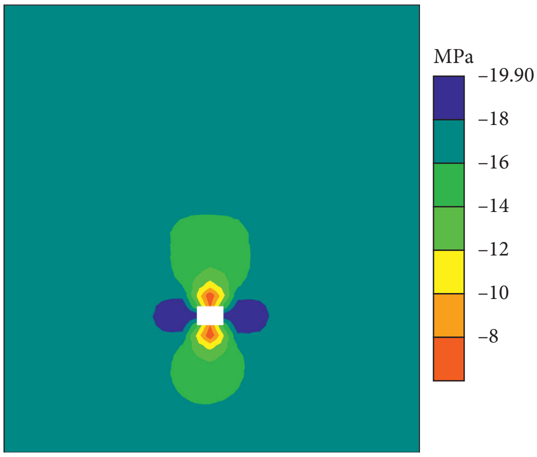

Figure 2: Vertical stress contour in return airway.

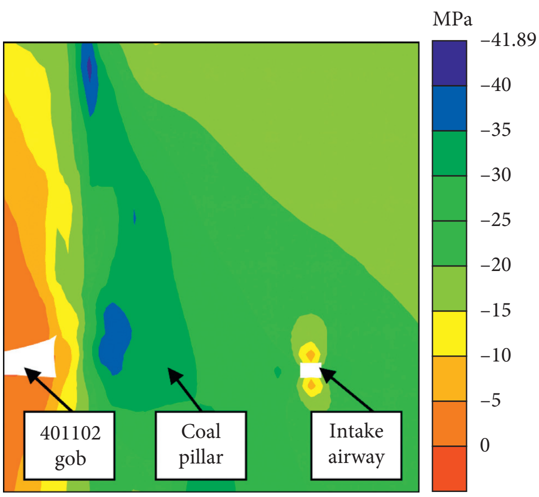

Figure 3: Vertical stress contour in intake airway.

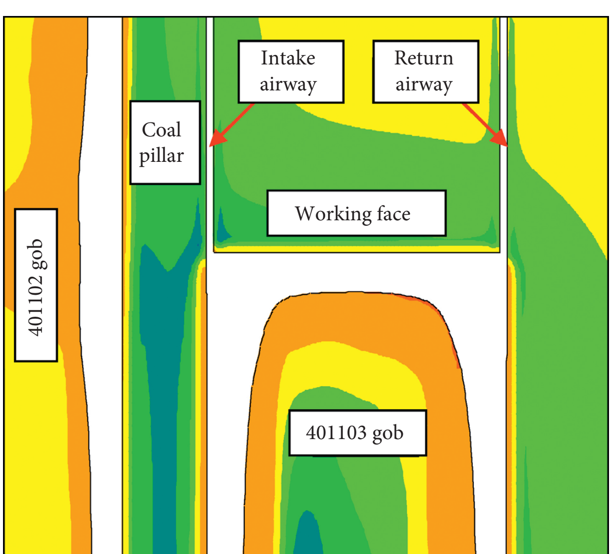

Figure 4: Vertical stress contour during mining.

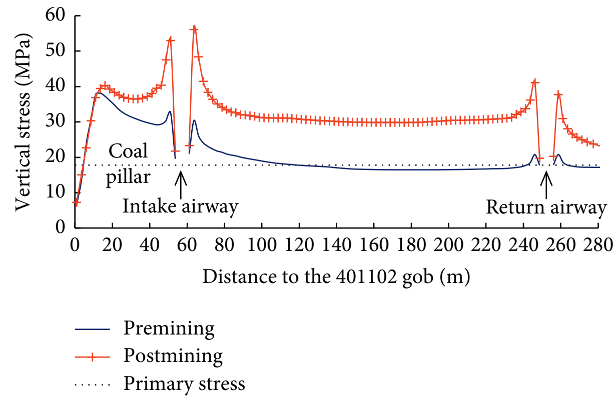

Figure 5: Contrast curve of abutment pressure between premining and postmining of the working face.

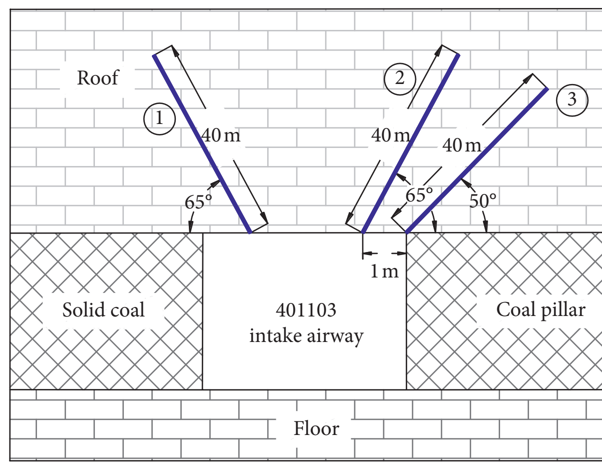

Figure 6: Sketch map of presplitting blast in roof.

away from the floor of roadway. They are parallel to coal seams and perpendicular to coal walls. All holes are arranged in one row. Depth, diameter, and interval between two holes are 20 m, 113 mm, and 1.4 m, respectively.

6.1.3. Coal Seam Water Injection. Water injection holes are constructed from the inner wall of the intake airway to coals on the working face, with an elevation of 7°. Depth and diameter of the holes are 115 m and 113 mm, respectively. The casing pipe is 15 m long and the space between two holes is 7 m. Water injection pressure is 6–15 MPa and water injection time is over 30 h.

6.1.4. Pressure Relief through Large-Diameter Pores at Bottom Corners. With respect to the pressure relief strategy through large-diameter pores at bottom corners, two holes are drilled on the floor. Elevations, depth, diameter, and interval are 65°, 10 m, 113 mm, and 1.4 m, respectively.

6.1.5. Pressure Relief through Blasting at Bottom Corners. With respect to the pressure relief strategy through blasting at bottom corners, two holes are drilled on the floor.

Elevation, depth, diameter, and sealing length are 45°, 10 m, 94 mm, and 8.4 m, respectively. Charging length, charging load, and interval between two holes are 1.6 m, 4.4 kg, and 3 m, respectively.

6.2. Regional Prevention Technologies

6.2.1. Narrow Coal Pillar for Roadway Protection for Gob-Side Advancing. Nowadays, wide coal pillar for roadway protection is highly appreciated in mine areas in Western China to separate gas from adjacent mining areas and prevent spontaneous combustion of coal seams, thus relieving the influences of abutment pressures on the adjacent working face [5]. A 54 m-wide coal pillar for roadway protection was preset in the intake airway on the 401103 working face of Hujiahe Coal Mine. This coal pillar not only is incapable of assuring the stability of surrounding rocks in the roadway but also causes a great waste of coal resources. Therefore, the use of narrow coal pillars on other working faces during gob-side advancing is suggested. The basic concept of a narrow coal pillar is "separation only and no load bearing." In other words, the narrow coal pillar only separates the space of the working face from the mining area and bears no loads because it has been crushed. As a result, the narrow coal pillar has no rock burst risks.

6.2.2. Layer Mining or Fully Mechanized Top-Coal Caving Face with Premining Top Layer. The fully mechanized top-coal caving face inevitably causes significant sectional expansion in adjacent mining roadways, which intensifies mining influences and worsens the appearance of mine ground pressure [4]. The main roof on the 401103 working face is formed by thick and hard sandstones, which require layer mining or fully mechanized top-coal caving face with a premining top layer. These mining technologies are similar to protective seam mining. Upper layer mining destroys the integrity of the hard roof. It not only releases abundant elastic energies that have been accumulated in the roof but also unloads stresses on the floor and protects the lower layer mining [22].

7. Conclusion

(1) Rock burst risks of the 401103 working face in Hujiahe Coal Mine are sensitive to mining depth, geological structure, outburst proneness of coal strata, roof strata structure, and mining influences from the adjacent working face and current working face.

(2) A very high stress concentration is formed in the coal pillar due to the collaborative effects of the front abutment pressure on the working face and the lateral abutment pressures on the gob during the 401103 working face advancing front abutment. The coal pillar is in a limit equilibrium state with the decrease of elastic zone.

(3) According to microseismic monitoring results, the seismic sources of historical rock burst events during mining of the 401103 working face are concentrated in places surrounding the section coal pillars. Rock burst events occur in the intake airway of the working face.

(4) Focusing on high rock burst risks occurring in the intake airway of 401103 working face, some local seismic dissipation measures are adopted, including pressure relief through presplitting blasting in roof, pressure relief through large-diameter pores in coal seam, coal seam water injection, pressure relief through large-diameter pores at bottom corners, and pressure relief through blasting at bottom corners. Moreover, some regional prevention technologies are proposed, such as using narrow coal pillar for roadway protection during gob-side advancing, layer mining, and fully mechanized top-coal caving face with premining top layer.

Data Availability

The 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.

Acknowledgments

This work was supported by the Institute of Energy, Hefei Comprehensive National Science Center (19KZS203), State Key Research Development Program of China (2019YFC1904304), and National Natural Science Foundation for Young Scientists of China (51604008), all of whom are gratefully acknowledged.

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