Geomechanics and Engineering, *Vol. 20, No. 5 (2020) 447-459*
DOI: https://doi.org/10.12989/gae.2020.20.5.447

Study on rockburst prevention technology of isolated working face with thick-hard roof

Chuanyang Jia*[1,2], Hailong Wang**[1b], Xizhen Sun[1], Xianbin Yu[1] and Hengjie Luan[3]

[1]*School of Civil Engineering and Architecture, Linyi University, Linyi 276000, China*
[2]*Linyi City Key Lab of Appraisement and Strengthening in Building Structures, Linyi 276000, China*
[3]*College of Mining and Safety Engineering, Shandong University of Science and Technology, Qingdao 266590, China*

(Received October 23, 2019, Revised February 3, 2020, Accepted February 12, 2020)

Abstract. Based on the literature statistical method, the paper publication status of the isolated working face and the distribution of the rockburst coal mine were obtained. The numerical simulation method is used to study the stress distribution law of working face under different mining range. In addition, based on the similar material simulation test, the overlying strata failure modes and the deformation characteristics of coal pillars during the mining process of the isolated working face with thick-hard key strata are analyzed. The research shows that, under the influence of the key strata, the overlying strata formation above the isolated working face is a long arm T-type spatial structure. With the mining of the isolated working face, a series of damages occur in the coal pillars, causing the key strata to break and inducing the rockburst occurs. Combined with the mechanism of rockburst induced by the dynamic and static combined load, the source of dynamic and static load on the isolated working face is analyzed, and the rockburst monitoring methods and the prevention and control measures are proposed. Through the above research, the occurrence probability of rockburst can be effectively reduced, which is of great significance for the safe mining of deep coal mines.

Keywords: thick-hard strata; isolated working face; overlying strata structure; similar material simulation; rockburst

1. Introduction

Rockburst and gas outbursts are typical dynamic disasters in coal mines (Christopher 2016, Panthi 2012, Mitri 2007, Zhang *et al.* 2017, 2018). In shallow mining, disasters such as rockburst, gas outburst, spontaneous combustion and mine water inrush occur singly. As the coal mine is excavated into the deep underground, in-situ stress, gas stress, grinding temperature, water inflow, as well as mining disturbances increase, while coal permeability decreases. Thus, gas is difficult to be extracted. At the same time, the properties of coal-rock mass in deep are significantly different from the shallow, and its mechanical behavior is nonlinear, causing the rockburst and gas outburst accidents are more serious. In deep mining, disasters such as rockburst, gas outburst, spontaneous combustion and mine water inrush are the compound occurrence. The disaster situation of deep mining is shown in Fig. 1.

In recent years, with the mining depth and intensity increase, geological conditions and surrounding areas are extremely complex in the working face, causing the rockburst frequent occurrence (Dou *et al.* 2009, Guo *et al.* 2019, Lawson *et al.* 2017). Rockburst poses a great threat to safe mining and the security of miners, under the circumstance of safe mining advocated in China, it is necessary to further improve the safety coefficient and reduce the risk of rockburst. However, in the current mining conditions, the rockburst risk is more prominent in isolated working faces, and rockburst prevention has become one of the major problems in the mining industry. According to the statistical analysis of rockburst accidents by relevant departments, the rockburst accidents of the isolated working face are increasing. Especially the isolated working face is disturbed by factors such as thick-hard strata (Dou and He 2012, Li *et al.* 2014, Jiang and Xu 2018, Ning *et al.* 2017, Guo *et al.* 2016, Mu *et al.* 2006) and large mining depth, resulting in the mining environment is more complicated and it is more challenging for safe mining. Taking the destruction accident of track roadway in Baodian coal mine as a case, the accident analysis shows that there exists a thick-hard sandstone layer above the coal seam, due to the small mining range, resulting in the large-scale suspended roof on the isolated working face. With the mining of the isolated working face, due to a series factors such as the gob range expansion, mining, coal pillar strength reduction, causing the key strata to break and large-scale overlying strata moving downwards, which leads to compressing gas in the gob to form a shock wave that destroyed track roadway.

Combined with the accident case of the isolated working face, the degree of rock pressure behavior in the mining face depends on the failure morphology and the key strata movement (He *et al.* 2010, Lu *et al.* 2016, Guo *et al.* 2017, Qian *et al.* 1996, Guo *et al.* 2019). Due to the special

∗Corresponding author, Ph.D.
E-mail: jiachuanyang@lyu.edu.cn
∗∗Co-Corresponding author, Ph.D.
E-mail: wanghailong@lyu.edu.cn

http://www.techno-press.org/?journal=gae&subpage=7 ISSN: 2005-307X (Print), 2092-6219 (Online)

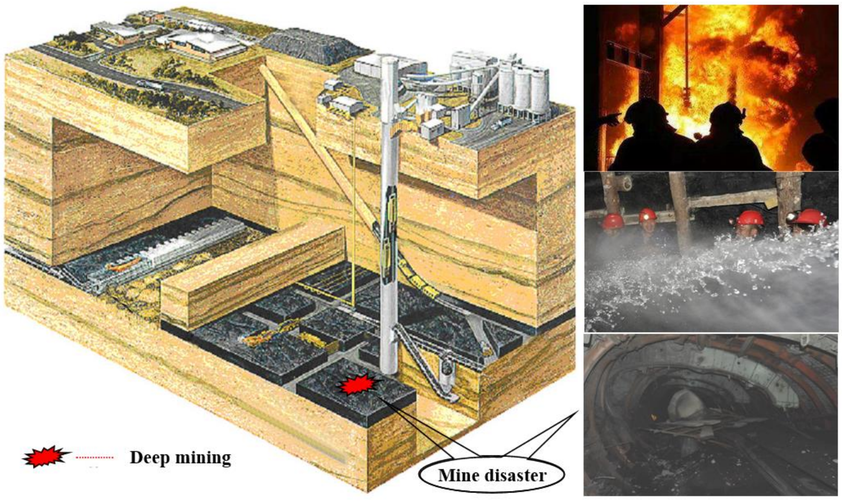


Fig. 1 Deep mining map of the working face

surrounding rock structure of the isolated working face, the movement law of the overlying strata is different from the ordinary working face. However, the study on the overlying strata fracture morphology, evolution law and rockburst instability mechanism of the isolated working face under the action of thick-hard key strata is still incomplete, which limits the rockburst prediction and prevention. Based on numerical simulation, experimental and theoretical analysis methods, this paper studies the overlying strata structure fracture morphology and the surrounding rock stress variation during the mining process of isolated working face, and discusses the relationship between overlying strata structure and rockburst, so as to take effective measures to avoid the occurrence of rockburst. Therefore, in order to make the most use of coal resources, it is necessary to study the rockburst prevention and control technology of the isolated working face.

2. Paper publication status of the isolated working face

2.1 Article quantity analysis

Taking "isolated working face" as the keyword, Fig. 2 shows the papers on the isolated working face included in the database. It can be seen that the number of papers collected in the database from 1990 to 2002 was at a low level, the reason is that the mining technical level and mining methods, resulting in a small number of isolated working faces. The number of papers collected in the database from 2004 to 2008 is relatively stable, with an average of 15 papers per year. At this stage, with the improvement of mining technology, strip mining method is gradually promoted and applied, the scholar is encouraged to carry out research on the isolated working face, and the research content mainly involves the surrounding rock support, the research on rockburst is relatively rare. In 2008, the number of papers collected by the database has gradually increased, especially from 17 papers in 2008 to 93 papers in 2016, and the papers included in the database from 2013 to 2016 mainly involve the rockburst of the isolated working face, the main reason is that the shortage of coal resources, and the coal pillars recycling. At the same time, with the increase of mining depth, the risk of rockburst increased during the mining process of strip coal pillars, and the research on rockburst became hot.

2.2 Correlation statistical analysis of the isolated working face

To rationally understand the rockburst conditions, characteristics and prevention techniques of the isolated working face in China, the literature statistics method was used to search the published papers on CNKI (China National Knowledge Infrastructure) with the keywords of "rockburst" and "isolated working face". Taking "rockburst" as the keyword, a total of 4322 journal papers were retrieved. Through the analysis of the relationship network, the keywords related to rockburst included working face (WF), rockburst prevention (RBP) (Wang *et al.* 2018), rockburst tendency (RBT) (Tan *et al.* 2018), microseismic monitoring (MM) (Frid 2001, He *et al.* 2011, Jiang *et al.* 2010, Khademian *et al.* 2018), deep mining (DM), borehole pressure relief (BPR) (Sahara *et al.* 2017, Meier *et al.* 2013, 2015, Lee *et al.* 2016, Duan and Kwok 2016), isolated working face (IF) and geological structure (GS) (Sainoki and Hani 2015a, 2015b), etc. The proportion of corresponding papers was shown in Fig. 3(a), and the research content of these papers covered the occurrence location of rockburst, disaster-causing factors, monitoring methods, prevention measures. Taking the keywords of "isolated working face", the keywords related to rockburst (RB), gob (G), coal pillar width (PW), roadway surrounding rock (RR), supporting pressure (SP) and rockburst prevention (RBP), etc, and the proportion of corresponding papers was shown in Fig. 3(b). Through the retrieval and analysis of two keywords, the searched contents were not independent but interactive and compatible. It indicated that between rockburst and isolated working faces were closely related, and the problem of rockburst is more serious during the mining process of the isolated working face. At the

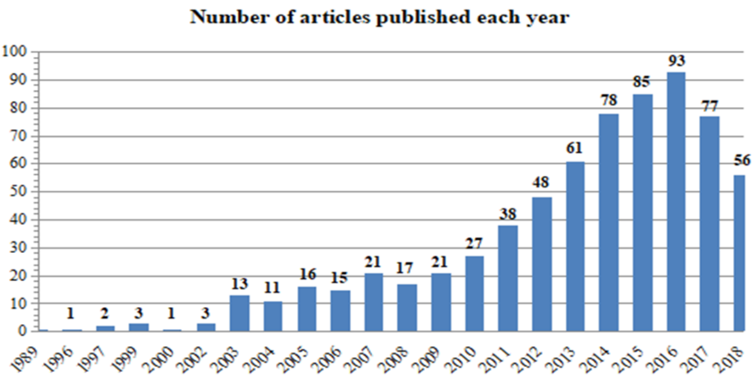
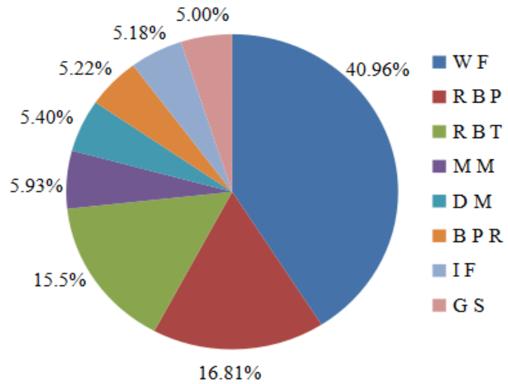
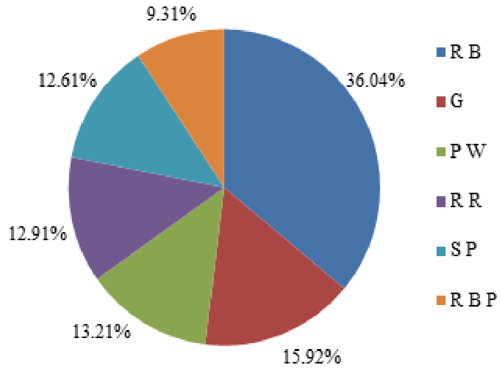


Fig. 2 Annual statistics of the papers included in the database



(a) Rockburst



(b) Isolated working face

Fig. 3 Keyword occurrence network diagram

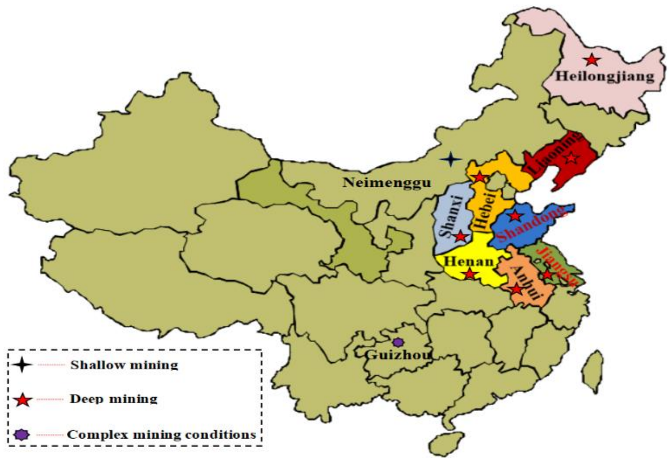


Fig. 4 The distribution map of rockburst coal mine

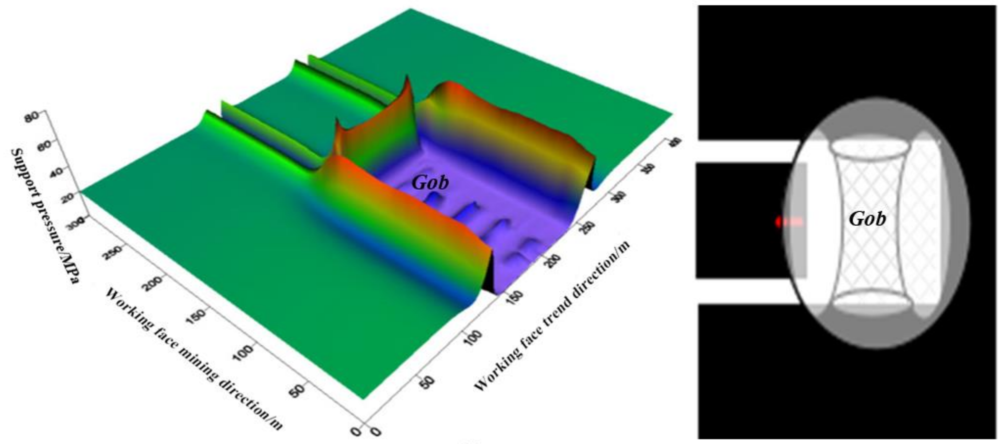
same time, the distribution of coal mines affected by rockburst is analyzed, the data show that the rockburst coal mine in China is mainly distributed in the provinces of Shandong, Heilongjiang, Liaoning, Henan, Jiangsu, Shanxi and Hebei, and the mines in these provinces reach deep mining conditions. While the coal resources in Neimenggu is rich and has a short mining life, and most of the coal mines in this region belong to the shallow mining range. Furthermore, the coal mining conditions in Guizhou province are complicated, thus safety mining should be strengthened. The coal mine distribution map is shown in Fig. 4.

3. Overlying strata structure characteristics and stress distribution of isolated working face

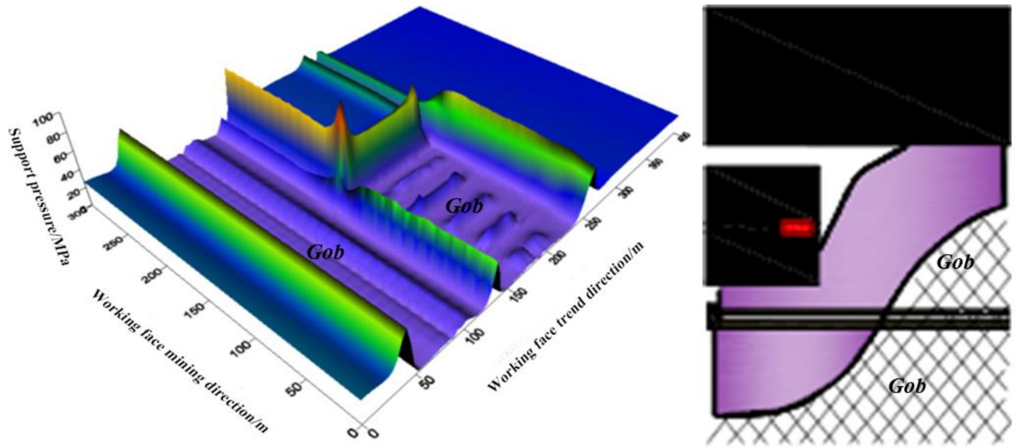
3.1 Stress distribution of working face under the influence of gob range

Overlying strata structure morphology and stress distribution of working face influenced by the gob range and position. Fig. 5 reveals the variation of distribution pattern, peak size and influence range of the supporting pressure in the working face as the gob range changes.

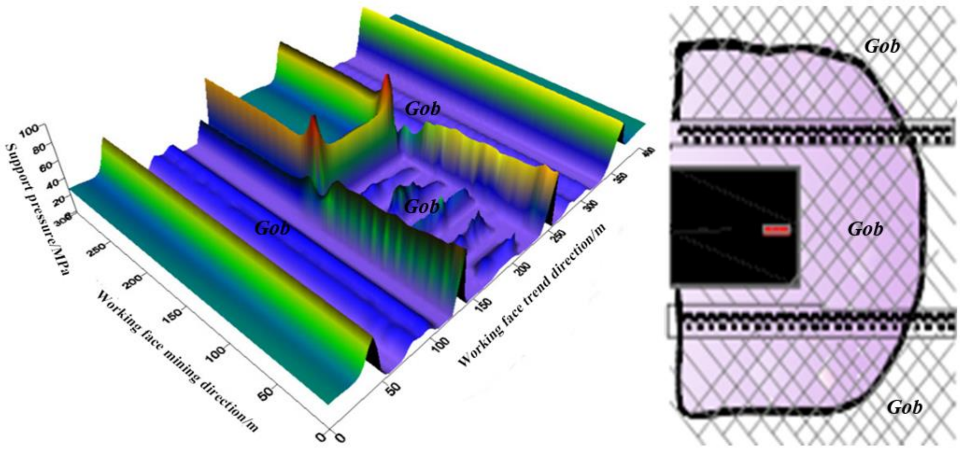
(1) When the gob position is behind the working face



(a) O-type



(b) S-type



(c) C-type

Fig. 5 Stress distribution under different gob position

(O-type), the distribution pattern of the advancing supporting pressure is symmetrical saddle shape, and the supporting pressure peak is relatively small. At the same time, stress concentration occurs at the corners of the roadway on both sides of the gob behind the working face, although it is located behind the working face, the broken of the roof in the gob will affect the working face mining.

(2) When the gob position is behind and one side of the working face (S-type), due to the superposition of the lateral supporting pressure and the advancing supporting pressure in the gob, causing the lateral supporting pressure on the side of the gob is higher than the solid coal side, and the supporting pressure distribution in front of the working face is asymmetrical saddle.

(3) When the gob position is behind and both sides of the working face (C-type), due to the gob range on both sides of the working face are equivalent, causing the lateral supporting pressure is similar. Furthermore, the stresses superimposed by the lateral supporting pressure and the advancing supporting pressure are symmetrical saddle

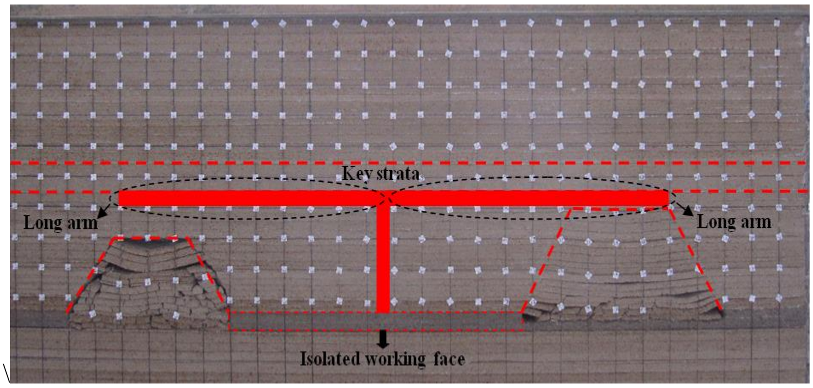


Fig. 6 T-type spatial structure of the isolated working face

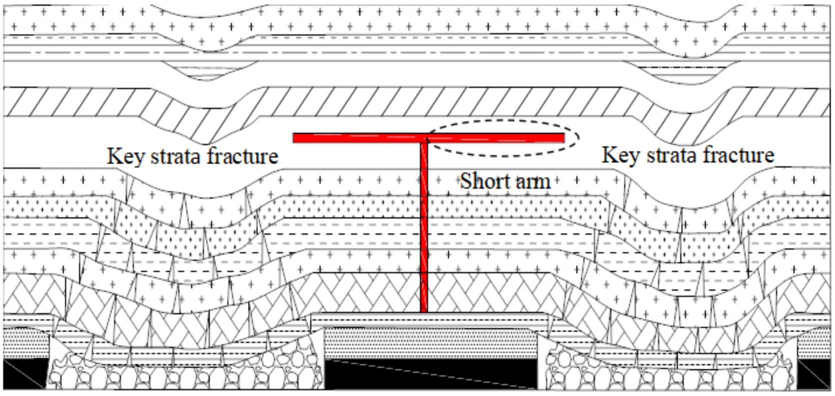


Fig. 7 Overlying strata fracture on both sides achieving sub-critical mining

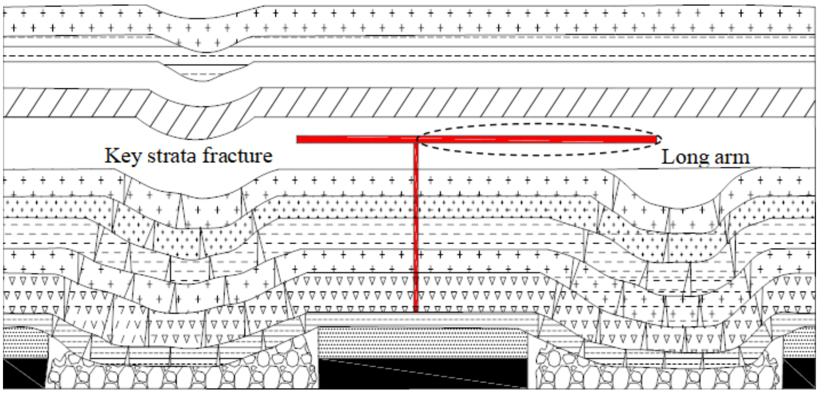


Fig. 8 Overlying strata fracture in only one side achieving sub-critical mining

shapes, and the stress peak phenomenon occurs at the corners of the coal wall.

3.2 Overlying strata structure characteristics of the isolated working face

At present, many scholars have carried out a lot of research on the overlying strata failure law in the mining process of working face (Lawson *et al.* 2017), and the research indicates that the damage height and failure mode of the overlying strata is related to the gob range. This paper studies the overlying strata failure characteristics of the isolated working face under the action of key strata and provides theoretical guidance for rockburst prevention and control.

3.2.1 Movement law of overlying strata

A similar material simulation test was used to analyze the overlying strata failure law, and the simulation test shows that under the influence of mining range, both sides working face of the isolated working face are sub-critical extraction, the fracture height of overlying strata is small. At the same time, due to the existence of thick-hard sandstone, the fracture height of the mining-induced overlying strata is limited, causing the overlying strata spatial structure of the isolated working face in the vertical section is long arm T-type, as shown in Fig. 6. At the same time, combined with other mining range on both sides working face of the isolated working face (both sides are critical extraction, one side is critical extraction and one side is sub-critical extraction), and the overlying strata of

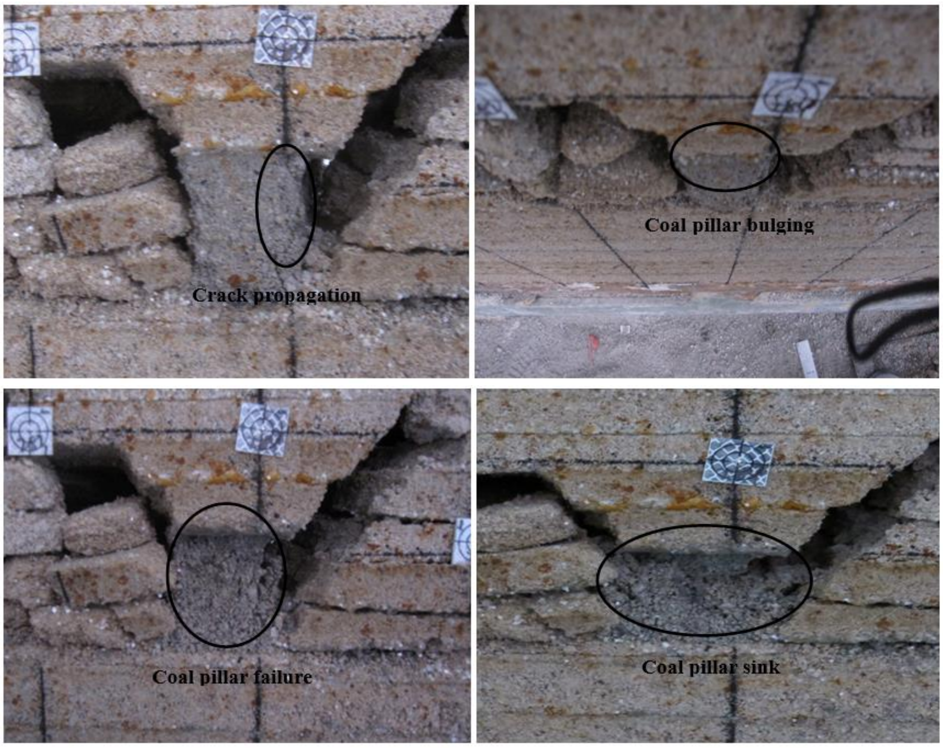


Fig. 9 Coal pillar failure characteristics

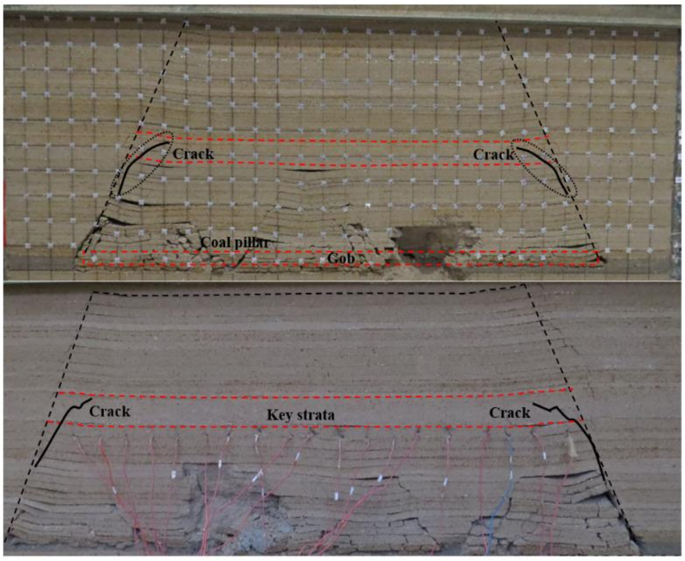


Fig. 10 Failure characteristics of the isolated working face

the isolated working face is a short arm T-type spatial structure and asymmetrical T-type spatial structure is shown in Figs. 7-8.

3.2.2 Movement law of overlying strata of the isolated working face

Fig. 9 shows the deformation and failure of the coal pillar in the roadway during the mining process of the isolated working face. With the mining range increase, the damage height of the overlying strata increases, causing the stress on the coal pillar to increases and the bulging phenomenon to occur. At this time, the thick-hard key strata are not damaged. With the mining of the isolated working face, the thick-hard sandstone suspension range increases, and a series of phenomena such as cracks and sinking to occur. At the same time, the bearing capacity of the coal pillars drops sharply, causing the gob connected to a whole, the thick-hard sandstone reaches the overhanging span limit and collapses. Finally, the overlying strata structure is destroyed and the whole test model sinks, as shown in Fig. 10.

4. Mechanism analysis of rockburst on the isolated working face

Stress concentration and energy accumulation are the premises of rockburst, and the overlying strata movement is the main inducing factor. When there is key stratum in the overlying strata, causing the instability of the long arm T-type spatial structure occurs, and the isolated working face in the status of high-stress concentration before the thick-hard strata fracturing, the static loading rockburst is easy to occur. With the mining range expansion of the working face, as the thick-hard strata reach the breaking span, the thick-hard strata move and settle rapidly under the action of self-weight and overlying strata loading, the mining stress concentration degree increasing, and the dynamic loading effect of the key strata fracturing, which is transformed into shock waves, and have a strong shock effect on surrounding rock masses, inducing the occurrence of high energy micro-seismic events, so the static and dynamic combined load inducing rockburst is easy to occur (He *et al.* 2010, Dou *et al.* 2015).

4.1 Static load analysis

Influenced by mining depth, fault structure and mining disturbance, the static load of the isolated working face is derived from the gravity stress field, the tectonic stress field, the supporting pressure, etc.

4.1.1 Self-weight stress field

Before the isolated working face mining, the main load comes from the self-weight stress field formed by the self-weight of the overlying strata. Using the theory of continuum mechanics, the self-heavy stress field is expressed as Eq. (1).

$$\sigma_w = \sum_{i=1}^{n} \gamma_i h_i = \gamma H \tag{1}$$

where σ_w is vertical stress of self-weight stress field; γ_i is i layer volume force; h_i is the i layer thickness; γ is bulk density, generally γ = 2.5×10^3 kg/m^3; H is overlying strata total thickness.

4.1.2 Tectonic stress field

The field data shows that the horizontal stress and the self-weight stress field have a certain positive correlation, the expression Eq. (2) is as follows.

$$\sigma_{\mathrm{gs}} = \sigma_x = \sigma_y = \lambda \sigma_{\mathrm{z}} \tag{2}$$

where σ_x σ_y is horizontal stress of the tectonic stress field; λ is the lateral pressure coefficient.

According to the research, the relationship between elastic energy and stress in coal-rock mass under triaxial conditions is defined as Eq. (3).

$$E_s = \frac{\sigma_x^2 + \sigma_y^2 + \sigma_z^2 - 2\mu(\sigma_x\sigma_y + \sigma_y\sigma_z + \sigma_z\sigma_x)}{2E} \tag{3}$$

where E_s is elastic energy accumulated in the coal body; μ is Poisson's ratio; E is coal body elastic modulus.

It can be seen that as the horizontal stress in the coal body increases, the accumulate elastic strain energy increases, and the higher the static load level, causing the possibility of inducing rockburst increases.

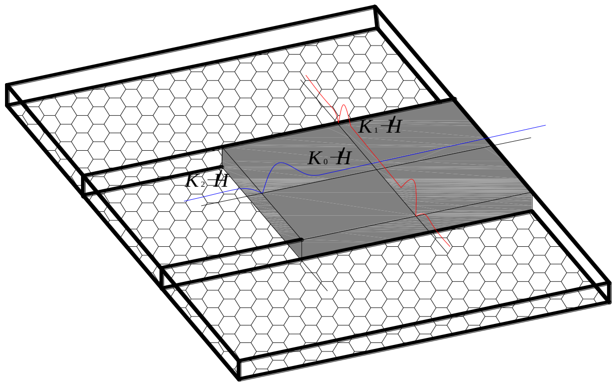


Fig. 11 The stress distribution of the isolated working face

4.1.3 Mining stress field

The isolated working face is in a special environment with three gobs and under the influence of the supporting pressure superposition, resulting in coal bodies on both sides of the gob in the stress concentration region. In addition, the mining stress field causes stress concentration in front of the working face, and the stress field distribution of the isolated working face is shown in Fig. 11.

4.2 Dynamic load source analysis

For isolated working face mining, dynamic load disturbances mainly come from pressure relief blasting, mining, drilling, overlying strata breaking (immediate roof, main roof, key strata breaking), coal pillar failure, fault slip. It can be seen from the similar material simulation test that the overlying strata are a long arm T-type structure before the isolated working face mining. As mining continues, the gob range increase and the suspension range of thick-hard sandstone is increased to cause cracks. When the area of the gob reaches the critical range, the thick-hard sandstone breaks and releases a large amount of elastic energy, which causes the rockburst to occur. It can be seen that the overlying strata movement (thick-hard sandstone breaking) is the main dynamic load factor for the rockburst.

4.3 Analysis of overlying rock movement induced rockburst of the isolated working face

From the view of energy (Li 1985, Dou *et al.* 2015), when the sum of the energy generated by the dynamic load and static load of the coal-rock is greater than the strength limit of the coal body, the rockburst occurs, the expression Eq. (4) is as follows.

$$\frac{dU_R}{dt} + \frac{dU_C}{dt} + \frac{dU_S}{dt} > \frac{dU_B}{dt} \tag{4}$$

where U_R is energy stored in surrounding rock; U_C is energy stored in coal mass; U_S is the energy of mine shock; U_B is the energy consumed when the rockburst occurs.

Energy stored in the coal and shock energy U is defined as Eq. (5).

$$U = \frac{(\sigma_s + \sigma_d)^2}{2E} \tag{5}$$

where σ_s and σ_d is the static and dynamic load in coal-rock mass.

The minimum energy U_{bmin} consumed when the rockburst occurs, the calculation equation is as follows Eq. (6).

$$U_{b\min} = \frac{\sigma_{b\min}^{\ 2}}{2E} \tag{6}$$

where σ_{bmin} is the minimum load when rockburst occurs.

When $\sigma_s + \sigma_d \geq \sigma_{bmin}$ causing rockburst occurs.

5. Rockburst monitoring

5.1 Static load monitoring and early warning

5.1.1 Drilling method

Through drilling holes with a diameter of 42 mm- 50 mm in the coal seam, when the hole enters the high-stress area of the coal body, dynamic characteristics appear during the drilling process, such as the part of coal body around the hole may suddenly squeeze into the hole, and accompanied by vibration, sound or micro-shock (Vardhan *et al.* 2009), discriminating the risk of rockburst according to the amount of coal powder discharged and its changing law, and the specific data for discriminating the risk of rockburst are shown in Table 1. Taking the isolated working face 3019 as an example, the entity coal in the working face was monitored with the single row arrangement, whose direction was parallel to coal seam and vertical to the roadway side. The borehole depth was 8 m, the drill pipe diameter was 42 mm, borehole spacing was 5 m, borehole spacing was 1.2 m from the roadway bottom plate.

5.1.2 On-line monitoring of rockburst

Within the advanced influence range of the rail roadway and transport roadway on the mining face, the layout of the real-time monitoring and warning system of rockburst was shown in Fig. 12. The first group of borehole stress gauges was set at 25 m away from the cut hole of the working face, the stations were arranged at the side of the mined coal body ahead of the rail roadway and transport roadway, and two measuring points were arranged at each group of stations (with interval of 2-3 m); the installation depth of borehole stress gauges was 14 m and 8 m respectively, which can monitor the stress of coal body within 150m ahead of the cut hole. Finally, the pressure data is automatically read by the monitoring system and real-time transmitted to the ground control room, showing the risk cloud map of rockburst (Fig. 13). In the actual project monitoring process, combined with the dangerous cloud map alarm position, and take a series of measures to effectively reduce the risk of rockburst.

5.2 Dynamic load monitoring and early warning

The microseismic monitoring system can provide early warning of dynamic load sources, realize the long-distance (maximum 10 Km), real-time, dynamic and automatic monitoring of the vibration signal, and can calculate the time, energy and space of the rockburst (Pan *et al.* 2015, Wang *et al.* 2018, Stec 2007, Linkov 2005, Khademian *et al.* 2018). Taking the isolated working face 10302 as a case, to explain the application of microseismic monitoring system in the prevention and control of rockburst. With the advancement of the isolated working face 10302, the vibration concentrated region moving forward and upwards, and the vibration number on the floor of the gob is gradually increasing as shown in Fig. 14. At the same time, the microseismic events are concentrated on the track roadway side, the transport roadway side is small. Combined with similar material simulation experiments, the gob range on the track roadway side is small, which belongs to the sub-critical extraction range, and there are many roof collapse events. However, the gob range on the transport roadway side is large, causing the roof critical extraction and there are fewer collapse events. Therefore, with the increase of the mining disturbance and the gob range, the large range of overlying strata in the gob is suspended, which is easy to cause the roof integral movement, and the microseismic monitoring vibration frequency increases.

The energy distribution of microseismic events during mining is shown in Figs. 15-16. The energy less than 10^4J is mainly distributed behind the mining line of the working face, and there are small energy microseismic events in the roof and floor. With the mining range expansion, large energy microseismic events appear in front of the working face, indicating that the rock strata has a large range of fracture or damage under the action of the advancing supporting pressure. The energy more than 10^5J is mainly distributed in the working face of 10301 and 10302, and the strong microseismic events originate from the thick

Table 1 Drilling rate index of rockburst risk

Drilling depth / Coal seam thickness	1.5	1.5 ~ 3	3
Drilling rate index	1.5	2 ~ 3	≥4

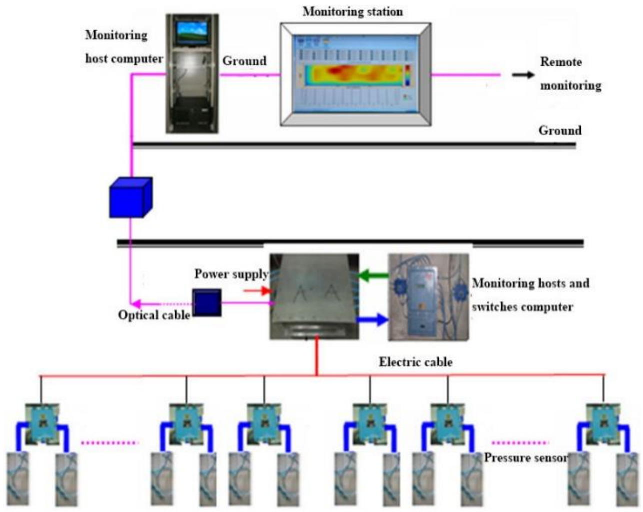


Fig. 12 Rockburst real-time monitoring and early warning system

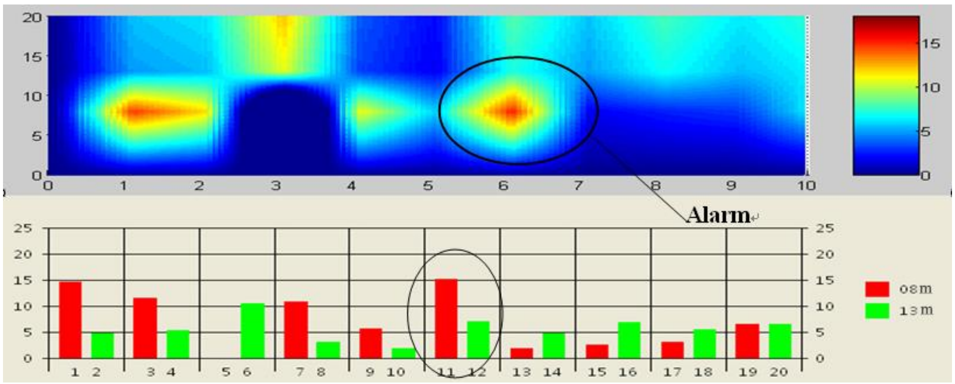


Fig. 13 Rockburst risk cloud map

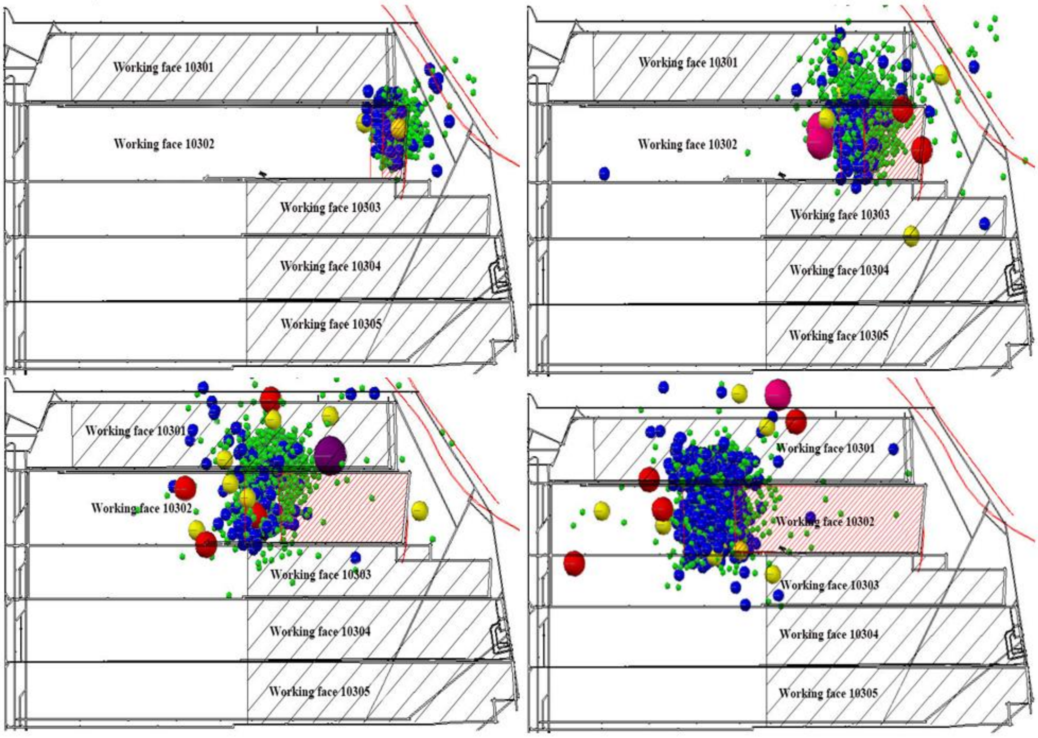


Fig. 14 Plane map of microseismic events on the isolated working face

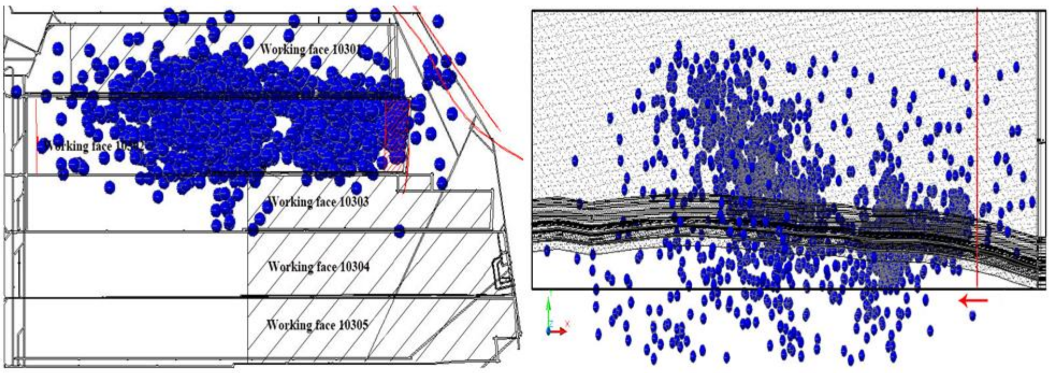


Fig. 15 Energy plane map of the microseismic events (10^3<E<10^4J)

sandstone fracture. From the above research, the microseismic monitoring data is consistent with the similar simulation test results. Therefore, the microseismic monitoring system is used in the mining process of the working face, which can provide basic data for the effective prevention and control of the rockburst, and ensure the efficient and safe mining of the coal mine.

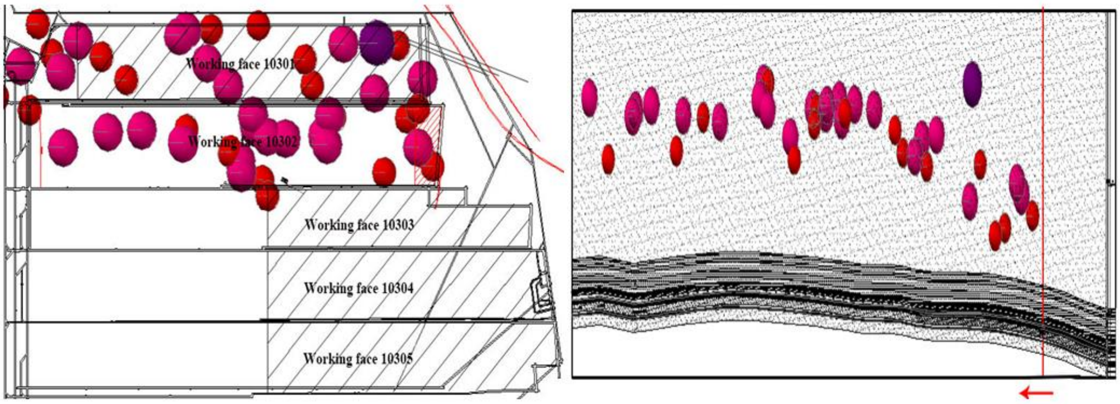


Fig. 16 The energy profile map of the microseismic event (E>105J)

6. Rockburst prevention and control of the isolated working face

Due to the complex mining environment of the isolated working face and many factors inducing the rockburst. Implement the technical means of “predicting-monitoring-dangerous zone pressure relief-examining-extraction-reforecasting”, and at the same time strengthen the safety management. The specific process of rockburst prevention and control of the isolated working face is shown in Fig. 17.

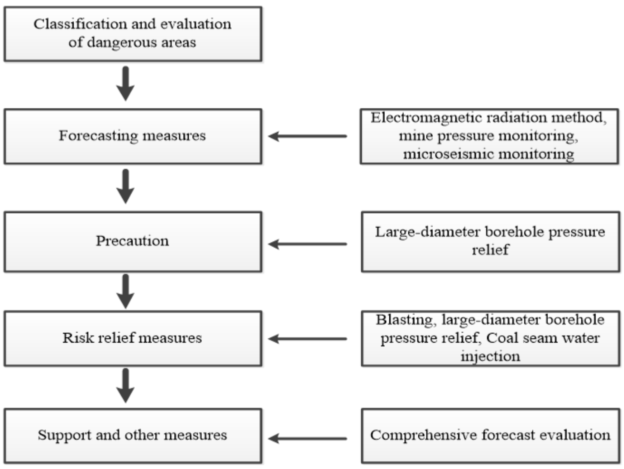


Fig. 17 The flow chart of rockburst prevention and control of the isolated working face

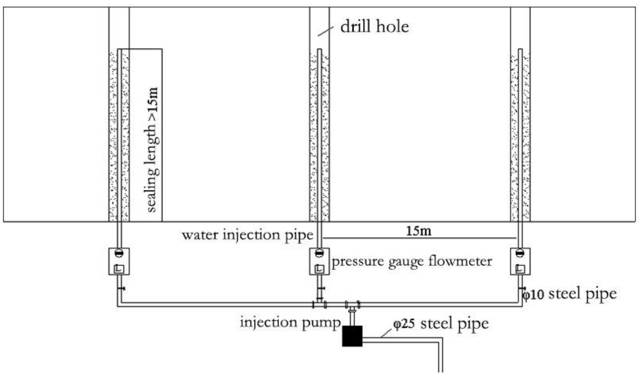


Fig. 18 Sketch of act press affusion system

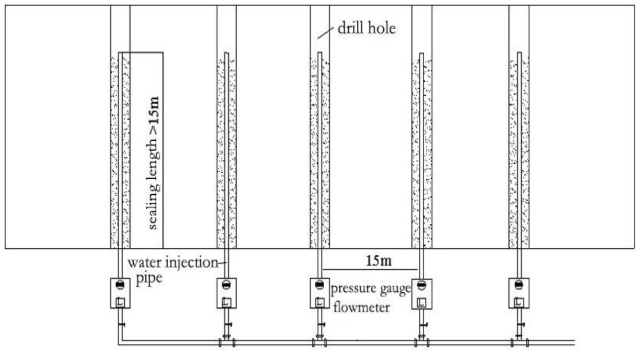


Fig. 19 Sketch of whist press affusion system

Table 2 Scheme of large-hole drill hole pressure relief

Danger degree	Drill hole depth	Drill hole diameter	Drill hole space
General danger zone	15 m	100-120 mm	3 m
Middle danger zone	15 m	100-120 mm	2 m
High danger zone	15 m	100-120 mm	1 m

6.1 Coal seam water injection

According to the mining technical conditions of the isolated working face, the coal seam water injection method is adopted to reduce the bursting tendency (Song *et al.* 2014). Using the two-way long borehole water injection method, namely the combination of long borehole high-pressure pre-injection and hydrostatic water injection. Figs. 18-19 show the schematic diagrams of the hydrodynamic water injection system and hydrostatic water injection system, respectively. Water injection holes were arranged near the entity coal, along the vertical roadway direction.

6.2 The large-diameter drill hole pressure relief technology

Combined with the isolated working face 3109 as an engineering background, the ZQJ-300/6 pneumatic column type drill was used for a large-diameter drill hole, and the hole diameter was 110 mm. According to the mining conditions and the dangerous area distribution of the rockburst, the large-diameter drilling hole pressure relief

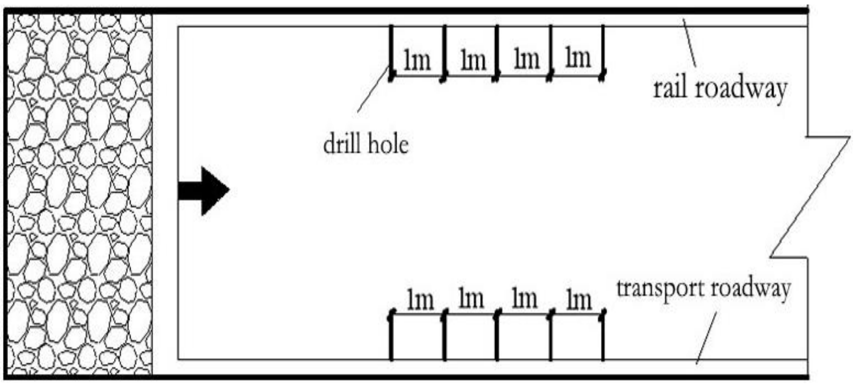


Fig. 20 Plane sketch of large-diameter drill hole pressure relief

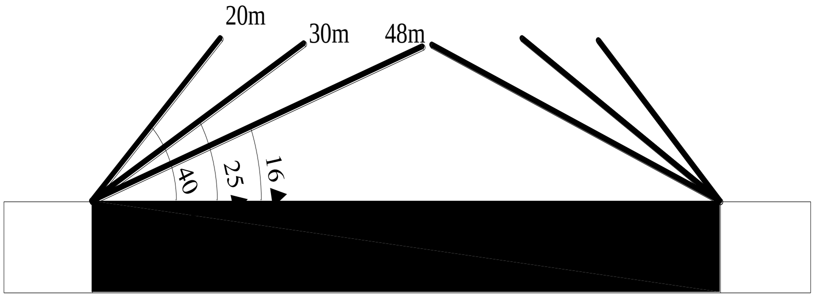


Fig. 21 Diagram of broken roof blasting and pressure releasing

technology was implemented. The scheme is shown in Table 2.

The layout plan of the large diameter boreholes is shown in Fig. 20. A row of pressure relief boreholes was constructed along the direction perpendicular to the roadway. The boreholes' elevation angle was 5°-8°, and the depth was 15m. If the pressure relief effect was not obvious, the density and depth of the drilling hole should be increased.

6.3 Drill hole pressure relief

Combined with the results of similar simulation experiments, the rockburst is greatly affected by the thick-hard strata, with the long-arm T-type spatial structure breaks, causing strong vibration and elastic energy release, and resulting in rockburst to occur. Therefore, it is necessary to carry out roof-breaking blasting, which will cause a large number of cracks in the overlying strata, and combine the actual geological conditions to design the thick-hard roof falling step, to avoid the formation of large dynamic pressure manifestation. The roof breaking blasting aimed to cause the roof breakage, so the drilling arrangement should be inclined to the working face, as shown in Fig. 21. The diameter of the drilling hole was more than 70 mm. The SM-II type small diameter water-gel explosive with the secondary coal mine permissible was used to cooperate with delayed electric detonator 1-5 section blasting, and the MFB-100 type detonator was used.

Through a series of measures to prevent and control the rockburst, during the mining process of isolated working face, the micro-seismic monitoring system was used for the continuous real-time monitoring. The data showed that there were many vibration times during the mining process, the vibration was mainly caused by small energy release, and the vibration energy was distributed between 10^2 and 10^4J, the earthquake events more than 10^4J were relatively few. For roof blasting was used to relieve pressure in dangerous areas, the working face had low vibration energy and stable energy release, which effectively avoided the occurrence of rockburst.

7. Conclusions

- The literature statistics shows that the isolated working face is closely related to the rockburst, and the rockburst mines in China are mainly distributed in the provinces of Shandong, Heilongjiang, Liaoning, Henan, Jiangsu, Shanxi and Hebei.
- The numerical simulation shows that the shape of the overlying strata structure is different due to the influence of the gob position, and it is mainly represented by O-type, S-type and C-type. Furthermore, the distribution of the advancing supporting pressure is symmetrical or asymmetrical saddle shape, and the peak on the gob side is higher than the solid coal side.
- Similar material simulation tests show that under the influence of the mining range and the thick-hard key strata, the overlying strata caving is insufficient, resulting in the long arm T-type overlying strata structure above the isolated working face. With the gob range increasing, the overlying strata expand upward, causing the stress above the coal pillar to increased and a series of phenomena such as cracking, bulging and sinking appear. Finally, the key

strata break and inducing the occurrence of rockburst.

• Combined with the dynamic and static combined load inducing rockburst mechanism, the main static load is derived from the self-weight stress field, geological structure stress field and supporting pressure. Furthermore, the dynamic load source comes from overlying rock fracture, coal pillar failure, fault slip. On this basis, the monitoring and early warning methods such as drilling method, on-line monitoring and electromagnetic radiometer are adopted, at the same time, using measures such as coal seam water injection, borehole pressure relief, roof cutting pressure relief can effectively reduce the probability of rockburst.

Acknowledgments

The research described in this paper was financially supported by the National Natural Science Foundation of China (No. 51704152, No. 51904149), the Natural Science Foundation of Shandong Province (No. ZR2017PEE018, ZR2019BEE013, ZR2019BEE065, and No. ZR2017BEE001).

References

Christopher, M. (2016), “Coal bursts in the deep longwall mines of the United States”, *Int. J. Coal Sci. Technol.*, **3**(1), 1-9. https://doi.org/10.1007/s40789-016-0102-9.

Dou, L.M. and He, H. (2012), “Study of OX-F-T spatial structure evolution of overlying strata in coal mines”, *Chin. J. Rock Mech. Eng.*, **31**(3), 453-460. https://doi.org/10.3969/j.issn.1000-6915.2012.03.003.

Dou, L.M., He, J. and Cao, A.Y. (2015), “Rock burst prevention methods based on theory of dynamic and static combined load induced in coal mine”, *J. China Coal Soc.*, **40**(7), 1469-1476. https://doi.org/10.13225/j.cnki.jccs.2014.1815.

Dou, L.M., Lu, C.P., Mu, Z.L. and Gao, M.S. (2009), “Prevention and forecasting of rock burst hazards in coal mines”, *Min. Sci. Technol.*, **19**, 585-591. https://doi.org/10.3969/j.issn.2095-2686.2009.05.007.

Duan, K. and Kwok, C.Y. (2016), “Evolution of stress-induced borehole breakout in inherently anisotropic rock: Insights from discrete element modeling”, *J. Geophys. Res. Solid Earth*, **121**(4), 2361-2381. https://doi.org/10.1002/2015JB012676.

Frid, V. (2001), “Calculation of electromagnetic radiation criterion for rockburst hazard forecast in coal mines”, *Pure Appl. Geophys.*, **158**(5-6), 931-944. https://doi.org/10.1007/PL00001214.

Guo, L.W., Latham, J. and Xiang, J.S. (2017), “A numerical study of fracture spacing and through-going fracture formation in layered rocks”, *Int. J. Solids Struct.*, **110-111**, 44-57. https://doi.org/10.1016/j.ijsolstr.2017.02.004.

Guo, W.J., Li, Y.Y., Yin, D.W., Zhang, S.C. and Sun, X.Z. (2016), “Mechanisms of rock burst in hard and thick upper strata and rock-burst controlling technology”, *Arab. J. Geosci.*, **9**(10), 561. https://doi.org/10.1007/s12517-016-2596-2.

Guo, W.Y., Gu, Q.H., Tan, Y.L. and Hu, S.C. (2019), “Case studies of rock bursts in tectonic areas with facies change”, *Energies*, **12**(7), 1-11. https://doi.org/10.3390/en12071330.

Guo, W.Y., Yu, F.H., Tan, Y.L. and Zhao, T.B. (2019), “Experimental study on the failure mechanism of layer-crack structure”, *Energy Sci. Eng.*, **7**(4), 2351-2372. https://doi.org/10.1002/ese3.407.

He, H., Dou, L.M., Gong, S., Zhou, P. and Xue, Z. (2010), “Rock burst rules induced by cracking of overlying key strata”, *Chin. J. Geotech. Eng.*, **32**(8), 1260-1265. https://doi.org/10.1016/S1876-3804(11)60004-9.

He, X.Q., Chen, W.X. and Nie, B.S. (2011), “Electromagnetic emission theory and its application to dynamic phenomena in coalrock”, *Int. J. Rock Mech. Min. Sci.*, **48**(8), 1352-1358. https://doi.org/10.1016/j.ijrmms.2011.09.004.

Jiang, F.X., Miao, X.H. and Wang, C.W. (2010), “Predicting research and practice of tectonic-controlled coal burst by microseismic monitoring”, *J. China Coal Soc.*, **35**(6), 900-904. https://doi.org/10.1016/S1876-3804(11)60004-9.

Jiang, J.Q. and Xu, B. (2018), “Study on the development laws of bed-separation under the hard-thick magmatic rock and its fracture disaster-causing mechanism”, *Geotech. Geol. Eng.*, **36**(3), 1525-1543. https://doi.org/10.1007/s10706-017-0406-6.

Khademian, Z., Nakagawa, M. and Ozbay, U. (2018), “Modeling injection-induced seismicity through calculation of radiated seismic energy”, *J. Nat. Gas Sci. Eng.*, **52**, 582-590. https://doi.org/10.1016/j.jngse.2018.02.013.

Lawson, H.E., Tesarik, D., Larson, M.K. and Abraham, H. (2017), “Effects of overburden characteristics on dynamic failure in underground coal mining”, *Int. J. Min. Sci. Technol.*, **27**(1), 121-129. https://doi.org/10.1016/j.ijmst.2016.10.001.

Lee, H., Moon, T. and Haimson, B.C. (2016), “Borehole breakouts induced in arkosic sandstones and a discrete element analysis”, *Rock Mech. Rock Eng.*, **49**(4), 1369-1388. https://doi.org/10.1007/s00603-015-0812-0.

Li, Y.S. (1985), “Rockburst mechanism and its preliminary application”, *J. China Univ. Min. Technol.*, **3**, 42-48. https://doi.org/CNKI:SUN:ZGKD.0.1985-03-005.

Li, Z.L., Dou, L.M. and Wang, G.F. (2014), “Rock burst characteristics and mechanism induced within an island pillar coalface with hard roof”, *J. Min. Saf. Eng.*, **41**(4), 519-524. https://doi.org/10.13545/j.issn1673-3363.2014.04.004.

Linkov, A.M. (2005), “Numerical modeling of seismic and aseismatic events in geomechanics”, *J. Min. Sci.*, **41**(1), 14-26. https://doi.org/10.1007/s10913-005-0059-3.

Lu, C.P., Liu, Y., Wang, H.Y. and Liu, P.F. (2016), “Microseismic signals of double-layer hard and thick igneous strata separation and fracturing”, *Int. J. Coal Geol.*, **160-161**, 28-41. https://doi.org/10.1016/j.coal.2016.04.011.

Meier, T, Rybacki, E., Reinicke, A. and Dresen, G. (2013), “Influence of borehole diameter on the formation of borehole breakouts in black shale”, *Int. J. Rock Mech. Min. Sci.*, **62**, 74-85. https://doi.org/10.1016/j.ijrmms.2013.03.012.

Meier, T, Rybacki, E., Reinicke, A. and Dresen, G. (2015), “Influence of bedding angle on borehole stability: A laboratory investigation of transverse isotropic oil shale”, *Rock. Mech. Rock. Eng.*, **48**(4), 1535-1546. https://doi.org/10.1007/s00603-014-0654-1.

Mitri, H.S. (2007), “Assessment of horizontal pillar burst in deep hard rock mines”, *Int. J. Risk Assess. Manage.*, **7**(5), 695-707. https://doi.org/10.1504/IJRAM.2007.014094.

Mu, Z.L., Dou, L.M., Zhang, G.W., Zhang, S.B., Li, Z.H. and Zhang, J. (2006), “Study of prevention methods of rock burst disaster caused by hard rock roof”, *J. China Univ. Min. Technol.*, **35**(6), 737-741. https://doi.org/10.1093/carcin/bgm010.

Ning, J.G., Wang, J. and Jiang, L.S. (2017), “Fracture analysis of double-layer hard and thick roof and the controlling effect on strata behavior: A case study”, *Eng. Fail. Anal.*, **81**, 117-134. https://doi.org/10.1016/j.engfailanal.2017.07.029.

Pan, J.F., Qin, Z.H., Wang, S.W., Yong, X. and Feng, M.H. (2015), “Preliminary study on early warning method based on weight comprehensive and different-load sources of coal bump”, *J.*

China Coal Soc., **40**(10), 2327-2335. https://doi.org/10.13225/j.cnki.jccs.2015.6012.
Panthi, K.K. (2012), "Evaluation of rock bursting phenomena in a tunnel in the Himalayas", *Bull. Eng. Geol. Environ*., **71**(4), 761-769. https://doi.org/10.1007/s10064-012-0444-5.
Qian, M.G., Miao, X.X. and Xu, J.L. (1996), "Theoretical study of the key strata in ground control", *J. China Coal Soc*., (03), 225-230. https://doi.org/10.13225/j.cnki.jccs.1996.03.001.
Sahara, D.P., Schoenball, M., Gerolymatou, E. and Kohl, T. (2017), "Analysis of borehole breakout development using continuum damage mechanics", *Int. J. Rock Mech. Min. Sci*., **97**, 134-143. https://doi.org/10.1016/j.ijrmms.2017.04.005.
Sainoki, A. and Hani, S.M. (2015a), "Effect of slip-weakening distance on selected seismic source parameters of mining-induced fault-slip", *Int. J. Rock Mech. Min. Sci*., **73**, 115-122. https://doi.org/10.1016/j.ijrmms.2014.09.019.
Sainoki, A. and Hani, S.M. (2015b), "Evaluation of fault-slip potential due to shearing of fault asperities", *Can. Geotech. J*., **52**(10), 1417-1425. https://doi.org/10.1139/cgj-2014-0375.
Song, D.Z., Wang, E.Y., Liu, Z.T., Liu. X.F. and Shen, R.X. (2014), "Numerical simulation of rock-burst relief and prevention by water-jet cutting", *Int. J. Rock Mech. Min. Sci*., **70**, 318-331. https://doi.org/10.1016/j.ijrmms.2014.05.015.
Stec, K. (2007), "Characteristics of seismic activity of the upper silesian coal basin in Poland", *Geophys. J. Int*., **168**(2), 757-768. https://doi.org/10.1111/j.1365-246X.2006.03227.x.
Tan, Y.L., Liu, X.S. and Shen, B. (2018), "New approaches to testing and evaluating the impact capability of coal seam with hard roof and/or floor in coal mines", *Geomech. Eng*, **14**(4), 367-376. https://doi.org/10.12989/gae.2018.14.4.367.
Vardhan, H., Adhikari, G.R. and Raj, M.G. (2009), "Estimating rock properties using sound levels produced during drilling", *Int. J. Rock Mech. Min. Sci*., **46**(3), 604-612. https://doi.org/10.1016/j.ijrmms.2008.07.011.
Wang, C.L., Chuai, X.S. and Shi, F. (2018), "Experimental investigation of predicting rockburst using Bayesian model", *Geomech. Eng*., **15**(6), 1153-1160. https://doi.org/10.12989/gae.2018.15.6.1153.
Zhang, C.G., Canbulat, I. and Hebblewhite, B. (2017), "Assessing coal burst phenomena in mining and insights into directions for future research", *Int. J. Coal Geol*., **179**, 28-44. https://doi.org/10.1016/j.coal.2017.05.011.
Zhang, H., Chen, L., Chen, S.G., Sun, J.C. and Yang, J.S. (2018), "The spatio temporal distribution law of microseismic events and rockburst characteristics of the deeply buried tunnel group", *Energies*, **11**(12), 3257. https://doi.org/10.3390/en11123257.

IC