Research Article

Analysis on the Influence of Fault Protection Coal Pillar Size on Rockburst

Hengqi Xin, Qinghai Li, Li Liu, Zhijun Liu, and Junmin Hou

Shandong Energy Xinwen Mining Group Co., Ltd., Tai’an 271000, China

Correspondence should be addressed to Qinghai Li; lqhxkjt@163.com

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Compared with other types of rockburst, fault rockburst releases the most energy and brings the hugest damage to the stope. Reasonable fault protection coal pillar can effectively prevent and control the occurrence of fault rockburst. Reasonable fault protection coal pillar (FPCP) can prevent and control the occurrence of fault rockburst effectively. Based on the engineering background of No. 7 mining area in a coal mine, this paper analyzes the reasonable coal pillar size on both sides of normal fault. Combined with the geological conditions in site, through the mechanical analysis of coal pillar stability, it is calculated that the critical FPCP size is 27.9 m for the working face in the upper wall and 39.0 m for the working face in the footwall. Through numerical simulation analysis, it is found that with the critical size of FPCP, the stress concentration coefficient in front of the upper wall working faces and footwall working faces is about 1.59. When the size of FPCP is smaller than the critical one, the difference of stress concentration coefficient between the two working faces (upper wall working face and footwall working face) is large, and the difference becomes larger and larger with the decrease of coal pillar size. When the size of FPCP is larger than the critical one, the difference of stress concentration coefficient between the two working faces (upper wall working face and footwall working face) is small, and the stress concentration coefficient of the two faces tends to be equal with the increase of coal pillar size. The rationality of coal pillar size is verified by field application, which provides a basis for the selection of FPCP in subsequent mining under similar conditions.

1. Introduction

In the process of coal mining in the deep, the occurrence frequency and intensity of rockburst are increasing under the interference of primitive environment (such as high geostress) and external factors (such as strong mining disturbance) [1]. Rockburst is a dynamic phenomenon of sudden and severe destruction of coal and rock mass around roadway or working face due to the instantaneous release of elastic energy, which is often accompanied by instantaneous displacement, throwing, loud noise, and air billow of coal and rock mass [2–4]. At present, rockburst is one of the most serious disasters threatening coal mine production [5].

The occurrence of rockburst is influenced by many factors, and the mechanism of rockburst is complex [6, 7]. Numerical simulation [8, 9] and physical test [10–12] are useful methods to explore the mechanism of rockburst. In numerical modeling, FLAC coupled with SPECFEM2D can be used in ground motion modeling near stope in underground mines [13]. And factors, such as the velocity wave fields, peak particle velocity contours, and amplification factors under different ratios of wavelength and roadway diameter [14], can be used to analyze the ground motion behavior around excavations. In physical tests, stepped loading and unloading on test block can be used to simulate the pillar burst phenomenon well [15]. The experimental results indicate that the degree of violence during failure is dependent on the unloading rate [16].

According to different occurrence mechanisms, there are many classifications of rockburst. For example, rockburst can be divided into two types, including strain rockburst and slip rockburst [17], or rockburst can be divided into three types, including coal compression rockburst, roof fracture rockburst, and fault dislocation rockburst [18], or rockburst can be divided into four types, including coal pillar type, hard roof type, fold structure type, and fault type [19], and other
classifications [20–23]. It can be seen that fault rockburst (i.e., rockburst caused by fault slip, which is caused by mining) is almost included in different classifications. Compared with other types of rockburst, fault rockburst releases the most energy and brings the highest damage to the stope \[6\].

When the rock mass containing faults is in a high stress state, the external disturbance urges the upper wall and footwall of faults to overcome friction resistance and slide \[10\] and then induces fault rockburst. The essence of fault rockburst is the instability of the interface between the upper wall and footwall of faults, which is mainly affected by the fault dip angle \[24\], the strength and roughness of the interface, the properties of fillings, and the stress state of rock mass and external disturbances. In the process of fault sliding, due to the structural difference between the two walls of the fault, the two walls of the fault will show different movement characteristics. The research shows that the footwall of fault mining has higher impact risk than the upper wall of fault mining \[25\].

In view of the severity and danger of fault rockburst, the effective early warning of fault rockburst is very significant to reduce the impact. According to the change law of mining stress, microseismic signal, electromagnetic radiation signal, acoustic emission signal \[26, 27\], and other parameters before fault rockburst, comprehensive early warning can be carried out for fault rockburst. When faults are included in the advancing range of the working face, the methods of large diameter drilling and coal seam water injection can be used to relieve the superposition of mining stress and further control the occurrence of fault sliding impact \[28, 29\].

At the same time, as the working face approaches the fault, the degree of mining influence on the fault gradually increases. If the coal pillars on both sides of the fault are set unreasonably, the fault will be activated and then rockburst will be induced. Therefore, setting reasonable fault protection coal pillar (short as FPCP) will also play an important role in preventing and controlling the fault rockburst. When selecting the size of coal pillar, if the size of coal pillar is too large, it will cause waste of resources, and if the size of coal pillar is too small, it will be difficult to prevent fault rockburst. In view of this, this paper takes No. 7 mining area of a coal mine as the engineering background. There are a lot of normal faults in No. 7 mining area, and the coal seam has impact tendency. The upper wall working face and footwall working face will be arranged in the mining process. In this paper, the reasonable size of coal pillar without impact danger is determined by mechanical analysis of coal pillar stability, and the FLAC3D numerical calculation model of mining in upper wall working face and footwall working face is further established. The evolution law of vertical stress in working face with 10 m, 20 m, 30 m, 40 m, and 50 m pillar sizes is simulated and analyzed, which provides basis for the prevention and control of fault rockburst in the field.

2. Background of the Project

In No. 7 mining area of a coal mine, 3# coal seam is mined in the area. The depth of the coal seam is 930 m~1080 m, with an average depth of 1000 m. The thickness of the coal seam is 2.05~4.28 m, with an average thickness of 2.6 m. The coal seam structure is simple. According to the impact tendency test \[30\], the dynamic failure time of the coal seam is 189 ms, the elastic energy index is 4.74, the impact energy index is 0.785, and the uniaxial compressive strength is 16.2 MPa, which indicates that 3# coal seam has weak impact tendency. The roof strata are mainly mudstone, with a thickness of 3.8~36.88 m, averaging 21.0 m. According to the impact tendency test, the uniaxial compressive strength of the roof is 50.8 MPa and its bending energy index is 178.9 kJ, which indicates that the roof has strong impact tendency. The floor is mainly mudstone, with a thickness of 3.70~13.72 m, with an average of 10.0 m and the uniaxial compressive strength of 33.2 MPa. Mechanical parameters of the roof, floor, and coal seams are shown in Table 1. There are 36 faults found in No. 7 mining area, all of which are normal faults, including 26 faults with a drop greater than 8 m. All faults’ dip angle is about 45.

3. Mechanical Analysis of Coal Pillar

In the process of working face advancing in the upper wall of the fault, the force diagram of coal pillar is shown in Figure 1. The fault dip angle is \( \theta \), and the thickness of the direct roof is \( h \). It is assumed that the fault extends to the bottom of the basic roof. On FPCP, the vertical uniform load is \( q \). On the basic roof, the vertical uniform load is \( Q \). The length of the basic roof is \( L \). For FPCP, when the length is \( l_u \), the static equilibrium formula is

\[
QL = Qh \cot \theta + ql_u. \tag{1}
\]

Collated and obtained,

\[
q = \frac{(QL - Qh \cot \theta)}{l_u}. \tag{2}
\]

According to \[31\], when the vertical load reaches 1.5 times of the uniaxial compressive strength of coal seam, the coal seam is in danger of impact, i.e.,

\[
\frac{(QL - Qh \cot \theta)}{l_u} = 1.5\sigma_c. \tag{3}
\]

In the upper wall working face, when the coal seam is in danger of impact, the critical FPCP size is determined as

\[
l_u = \frac{(QL - Qh \cot \theta)}{1.5\sigma_c}. \tag{4}
\]

In the process of working face advancing in the footwall of the fault, the force diagram of coal pillar is shown in Figure 2. The fault drop is \( H \). For FPCP, when the length is \( l_f \), the static equilibrium formula is

\[
QL + Q(h - H) \cot \theta = ql_f. \tag{5}
\]
According to [31], when the vertical load reaches 1.5 times of the uniaxial compressive strength of coal seam, the coal seam is in danger of impact, i.e.,

$$q = \frac{(QL + Q(h - H) \cot \theta)}{l_f}. \quad (6)$$

According to [31], when the vertical load reaches 1.5 times of the uniaxial compressive strength of coal seam, the coal seam is in danger of impact, i.e.,

$$q = \frac{(QL + Q(h - H) \cot \theta)}{l_f} = 1.5 \sigma_c. \quad (7)$$

In the footwall working face, when the coal seam is in danger of impact, the critical FPCP size is determined as

$$l_f = \frac{(QL + Q(h - H) \cot \theta)}{1.5 \sigma_c}. \quad (8)$$

The average depth of coal seam is 1000 m, and the average bulk density of overlying strata is $2.3 \times 10^4$ N·m$^{-3}$; then

$$Q = 2.3 \times 10^4 \times 1000 = 23 \times 10^6 \text{ N/m.} \quad (9)$$

According to geological conditions, $\theta$ is taken as 45°, and faults with drop greater than 8.0 m account for 72.2% of all faults. Thus, the fault drop $H$ is taken as 8 m. According to the data of adjacent mining area, the thickness of the direct roof is about 10 m. Therefore, $h$ is taken as 10 m. In the adjacent mining area, the primary fracture length of the basic roof is 40 m, and the periodic fracture length is 12 m. The longer the length of the basic roof, the greater the stress on the FPCP. Thus, the length $L$ of the basic roof is taken as 40 m. The uniaxial compressive strength of coal seam is 16.5 MPa (Table 1). It is calculated that when the coal seam is in danger of impact, for the upper wall working face, the critical FPCP size is 27.9 m, and for footwall working face, the critical FPCP size is 39.0 m.

It can be seen that in the field production, under the same mining conditions, the critical size of FPCP of footwall working face is larger than that of upper wall working face. That is, the footwall working face is more severely affected by faults, and the width of FPCP needed to ensure no impact danger is larger.

### 4. Numerical Simulation Analysis of Coal Pillar Stability

#### 4.1. Establishment of Numerical Model

The FLAC3D calculation model of the upper wall working face and footwall working face is shown in Figure 3. The model size is 151 m x 20 m x 52 m in length x width x height, and the thickness and mechanical parameters of each rock stratum are shown in Table 1. The bottom boundary of the model is fixed, and the top boundary is set as a free boundary. The rock layer 1000 m above the model is applied to the top of the model in the form of vertical load. The average bulk density of the overlying rock layer is $2.3 \times 10^4$ N·m$^{-3}$. It is calculated that

| Rock strata                  | Thickness (m) | Density (kg/m$^3$) | Elastic modulus (GPa) | Uniaxial compressive strength (MPa) | Poisson’s ratio | Cohesion (MPa) | Internal friction angle (°) | Tensile strength (MPa) |
|-----------------------------|---------------|--------------------|-----------------------|-------------------------------------|----------------|----------------|----------------------------|------------------------|
| Medium sandstone            | 18.4          | 2410               | 33.5                  | 46.5                                | 0.25           | 3.45           | 33                         | 5.15                   |
| Mudstone and sandy mudstone | 21.0          | 2450               | 38.4                  | 50.8                                | 0.24           | 4.62           | 35                         | 5.62                   |
| 3# coal seam                | 2.6           | 1320               | 3.5                   | 16.2                                | 0.32           | 1.25           | 30                         | 1.45                   |
| Mudstone                    | 10.0          | 2380               | 30.5                  | 33.2                                | 0.27           | 3.15           | 32                         | 3.53                   |

Table 1: Rock mechanical parameters of strata.
the uniform load applied to the top of the model is 22.1 MPa. The horizontal stress obtained by field test is about 0.8 times of the vertical stress, and the uniform load of 17.68 MPa is applied horizontally on both sides of the model. Strata on both sides of the fault are discontinuous, and the filling strength is lower. The fault is expressed by weak strata with lower mechanical parameters, which are taken as 0.1 times of coal seam parameters. The upper wall working face and footwall working face are all set as 50 m, 40 m, 30 m, 20 m, and 10 m. Excavate from the boundary of the model to the coal pillars with set sizes in turn, and stress measuring line was set to monitor the evolution law of vertical stress under coal pillars with different sizes. Stress measuring line was set at the interface between coal seam and direct roof along the length of model. And the stress measuring line was set in the middle of the width of the model.

4.2. Simulation Result Analysis

4.2.1. Analysis of Vertical Stress in Advancing of Upper Wall Working Face. The evolution nephogram of mining vertical stress in upper wall working face with different coal pillar sizes is shown in Figure 4, and the corresponding evolution curve is shown in Figure 5. During the advancing process of the working face, due to the influence of mining, the stress concentration is formed in the coal pillar in front of the working face, and the pressure relief zone appears in the fault due to the low strength of the filler. After crossing the fault, the stress returns to the original rock stress level. With the increase of the size of FPCP, the stress distribution in the coal pillar in front of the working face has obvious double peak characteristics. One peak is located near the fault, which is caused by the high tectonic stress at the fault, and the other is located near the coal wall, where the stress reaches the maximum value, which is caused by the superposition of the fault tectonic stress and the advanced abutment pressure in the working face. Statistics of peak stress and stress concentration coefficient in front of working face under 10 m, 20 m, 30 m, 40 m, and 50 m fault coal pillars are shown in Table 2. The original rock stress at the coal seam position is calculated by multiplying the buried depth by the average bulk density of the overlying strata, which is about 23.0 MPa. Stress concentration coefficients, which are obtained by peak stress divided by original rock stress, are 1.70, 1.63, 1.57, 1.53, and 1.49 at corresponding positions, respectively. The evolution trend of stress concentration coefficient is shown in Figure 6. It can be seen that with the increase of coal pillar size, the stress concentration coefficient gradually decreases, and with the working face approaching to the fault, the stress concentration degree in the coal pillar gradually increases, and the risk of rockburst gradually increases.
Figure 4: Continued.
4.2.2. Analysis of Vertical Stress in Advancing of Footwall Working Face. The evolution nephogram of mining vertical stress in footwall working face with different coal pillar sizes is shown in Figure 7, and the corresponding evolution curve is shown in Figure 8. During the advancing process of the working face, due to the influence of mining, stress concentration is formed in the coal pillar in front of the working face. Compared with the upper wall
working face, the internal stress of the coal pillar in front of the working face tends to be stable and then flat, without obvious double peak characteristics. This is because the FPCP is below the vertical projection of the fault, and the weak interlayer in the fault plays a certain buffering role, thus avoiding the occurrence of double peak. The statistics of peak stress and stress concentration coefficient in front of working face under 10 m, 20 m, 30 m, 40 m, and 50 m fault coal pillars are shown in Table 2. The stress concentration coefficients at corresponding positions are 2.26, 1.98, 1.75, 1.59, and 1.50, respectively. The evolution trend of stress concentration coefficient is shown in Figure 6, which is consistent with the upper wall working face. With the increase of coal pillar size, the stress concentration coefficient decreases gradually.

4.3. Comparative Analysis of Stress Concentration Coefficient of Upper Wall Working Faces and Footwall Working Faces. Comparing the evolution curve of stress concentration coefficient between the upper wall working face and footwall working face (Figure 6), it can be seen that the mining stress concentration coefficient of the footwall working face is larger than that of the upper wall working face. Combined with the above calculation and analysis, it is determined that the size of the boundary FPCP in the upper wall working face is 27.9 m, and that in the footwall working face is 39.0 m. At the position of critical FPCP, the stress concentration coefficient of the upper wall working faces and footwall working faces is about 1.59, which is shown by blue dashed line in Figure 6. When the coal pillar size is smaller than the critical coal pillar size, the stress concentration coefficient is greater than 1.59, and when the coal pillar size is larger than the critical coal pillar size, the stress concentration coefficient is less than 1.59. Meanwhile, it can be seen that the difference of stress concentration coefficient between the two working faces is larger when it is less than the critical coal pillar size and the same coal pillar size, and the difference is getting bigger and bigger with the decrease of coal pillar size, that is, when it is less than the critical coal pillar size, it is more likely to cause stress concentration in the mining of the footwall working face. However, when the coal pillar size is larger than the critical coal pillar size, the difference of stress concentration coefficient between the upper wall working faces and footwall working faces decreases at the same coal pillar size. With the increase of coal pillar size, the stress concentration coefficients of the two tend to be equal. For example, when the coal pillar size is 50.0 m, the stress concentration coefficients of the upper wall working face and footwall working face are 1.49 and 1.50, respectively. This is because with the increase of coal pillar size, the influence of fault tectonic stress gradually decreases and tends to disappear, and the mining influence degree of the two working faces is basically the same.

5. Application

When there is a normal fault in the mining process of the working face in No. 7 mining area of a coal mine, reset the open-off cut in the process of cross-fault mining in working face. For faults with a drop of less than 8 m, 30 m FPCP is reserved on the upper wall of fault and 40 m FPCP is reserved on the footwall of the fault (selection of reference mechanical analysis and numerical simulation results). For faults with a drop of more than 8.0 m, the size of FPCP has been appropriately expanded, and stress and microseismic monitoring are added during mining. In the normal advancing range of the working face, the microseismic energy is mostly in the range of $10^3$ J, and there is basically no early warning in online stress monitoring. When the two sides of the fault are close to the stop line and the new cut position, a spot of the energy monitored by microseisms is $10^4$ J, and a small number of early warnings occur in stress monitoring. The early warnings are cancelled after borehole pressure relief, and the microseismic and stress online monitoring returns to normal. Drilling pressure relief method is to drill holes on two sides of roadway at 1.5 m away from the roadway floor. The holes’ diameter is 100 mm, the drilling depth is 20 m, and the drilling spacing is 1.5 m. It can be seen that the upper wall FPCP is 30.0 m, and the footwall FPCP is 40.0 m, which can meet the requirements of the rockburst prevention in No. 7 mining area of a coal mine.

Table 2: Statistical table of peak stress and stress concentration coefficient.

| Coal pillar size (m) | 10  | 20  | 30  | 40  | 50  |
|---------------------|-----|-----|-----|-----|-----|
| Peak stress (MPa)   |     |     |     |     |     |
| Working face in upper wall | 39.2 | 37.5 | 36.1 | 35.1 | 34.3 |
| Working face in footwall  | 52.0 | 45.5 | 40.3 | 36.6 | 34.5 |
| Stress concentration coefficient |     |     |     |     |     |
| Working face in upper wall | 1.70 | 1.63 | 1.57 | 1.53 | 1.49 |
| Working face in footwall  | 2.26 | 1.98 | 1.75 | 1.59 | 1.50 |

Figure 6: Evolution curves of stress concentration coefficients.
Figure 7: Continued.
6. Conclusion and Discussion

When there is a fault in the advancing range of the working face, with the approach of the working face to the fault, the degree of mining influence on the fault gradually increases. When the coal pillars on both sides of the fault are set unreasonably, the fault will be activated and then rockburst will be induced. Based on the engineering background of No. 7 mining area in a coal mine, this paper analyzes the reasonable coal pillar size on both sides of the normal fault and obtains the main conclusions as follows:

(1) Through the mechanical analysis of coal pillar stability, it is obtained that the mining of footwall working face.

![Figure 7: Contour of vertical stress in footwall working face.](image)

![Figure 8: Evolution curves of vertical stress in footwall working face advancing.](image)
face is more severely affected by faults, and the size of FPCP is larger when ensuring no impact danger of coal seam. According to the specific stratum conditions of No. 7 mining area of a coal mine, the critical FPCP size is calculated to be 27.9 m in the upper wall working face and 39.0 m in the footwall working face.

(2) Combined with the geological conditions of No. 7 mining area, numerical analysis shows that the stress concentration coefficient of the upper wall working faces and footwall working faces is about 1.59 at the position of critical FPCP. When the coal pillar size is smaller than the critical coal pillar size, the stress concentration coefficient is greater than 1.59, and when the coal pillar size is larger than the critical coal pillar size, the stress concentration coefficient is less than 1.59. When the coal pillar size is smaller than the critical coal pillar size, the difference of stress concentration coefficient between the two working faces is bigger and bigger with the decrease of coal pillar size. When the coal pillar size is larger than the critical coal pillar size, the difference of stress concentration coefficient between the upper wall working faces and footwall working faces decreases with the same coal pillar size, and with the increase of coal pillar size, the stress concentration coefficient of the two working faces tends to be equal.

(3) Based on the results of mechanical analysis and numerical calculation, 30 m FPCP was set up on the upper wall of the fault and 40 m FPCP was set up on the footwall of the fault during the mining in No. 7 mining area. There was basically no abnormality in microseismic and stress online monitoring within the normal advancing range of the working face, which ensured the normal mining of the working face.

In addition, in the above mechanical analysis of coal pillar stability, the stability of coal pillar is mainly analyzed from the static point of view, and the reasonable FPCP size is determined. However, under the influence of dynamic load, the fault activation conditions are different from the activation mechanism under static load, and the FPCP size considering the influence of dynamic load needs further analysis. At the same time, this paper analyzes the stress situation and stress evolution law of the two working faces in the normal fault, and whether the mining influence of the two working faces in the reverse fault is consistent with the normal fault needs further study.

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 is no conflict of interest regarding the publication of this paper.

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