INTRODUCTION

Rockburst refers to the severe dynamic disaster caused by the sudden release of elastic strain energy of coal (rock) mass around a coalmine roadway or working face. Rockburst is often accompanied by instantaneous throwing of coal and rock, loud noises and air billow.\(^1,^2\) Rockburst hazards usually occur locally without influencing the general stability of the mine, threatening the safety of the personnel’s lives in this local area. A number of deaths and considerable economic loss have been caused by rockbursts.\(^3^5\) At present, over 190 coalmines in China have been identified with rockburst hazards, which is a serious threat to the safety of personnel’s lives and economic development.\(^1^5\) In recent years, rockburst accidents have occurred in some coalmines in China, and the corresponding cost has increased significantly.\(^1^5\) Therefore, the prevention and control of rockbursts is the primary task in coalmine safety management.

To prevent and control rockbursts, the international academic community has done a lot of research in this area, mainly focusing on rockburst triggering factors, triggering conditions, and prediction and control.\(^2^4\) In China, the research on rockburst is also very active. For example, Lian et al.\(^6^8\) studied the influence of the overlying strata structure and the stress-strain characteristics of the overlying strata on rockburst, and put forward the relationships between these and rockburst occurrence. However, the research on the design of rib pillars is less. In this study, a T-shaped overlying strata structure model was established, and the abutment stress in the rib pillar was determined. Then, the criterion for overall burst instability of the rib pillar was proposed. This criterion can be used as the criterion for water-seepage prevention. The proposed approach was used to design the width of a rib pillar in Yineng Coalmine located in Shandong Province, China. The analysis of the microseismic monitoring results and borehole drill cuttings show that the designed rib pillar with a width of 10 m was stable without water seepage during mining, indicating the width design method proposed in this study is effective.
tendency, among which over 50 mines are operating at a depth of over 800 m (ultradeep mines). With the continuous depletion of shallow coal resources and the gradually increasing mining intensity and depth, high-stress-induced rockburst hazards occur more and more frequently and seriously in China.

Scholars in China and abroad have carried out a lot of research on rockburst criteria, prediction, and prevention methods. The current research on the occurrence criteria for rockbursts is mainly divided into three categories: static stress criterion, static-dynamic-stress criterion, and energy criterion. The static stress criterion states that rockburst may occur if the static abutment stress exerted on the rock mass exceeds a limit value (usually 1.5 times as high as the uniaxial compressive strength of the rock). The static-dynamic-stress criterion evaluates rockburst hazards considering superposition of in situ geostress and dynamic stress caused by mining or tunneling. The energy criterion uses the accumulation and dissipation of elastic strain energy of the rock mass to study the mechanism of rockbursts. Recently, robust machine learning techniques have been widely applied in civil and mining fields, which inspire researchers use these advanced tools for predicting rockburst intensity (a four-class problem) and rockburst occurrence (a binary problem). In addition, during mining or tunneling, advanced monitoring techniques have been employed to predict rockburst hazards, such as microseismic monitoring, computed tomography technology, and electromagnetic radiation methods. These techniques can monitor fracture or energy release of rock in real time and thus provide useful information for prediction of rockbursts. In terms of control of rockbursts, several techniques have been recommended for rockburst mitigation, such as changing mining methods (eg, pillarless mining), ground preconditioning (eg, water injection, destress blasting, and destress drilling), and use of energy-absorbing bolts.

However, the abovementioned rockburst prediction and prevention methods are passive methods, which do not fully take into account geological conditions, mining technology, stope range, coal and rock states, etc. Therefore, rockbursts still occur frequently in ultradeep mines. To mitigate rockbursts, this study applies superhigh-water backfill mining as an active rockburst-control measure. Backfilling the gob can prevent fracture of overlying strata and thus reduce the abutment stress applied on the longwall panel, roadways, and rib pillars. A variety of backfilling methods have been applied in underground coalmines, such as hydraulic backfilling, paste backfilling, and solid backfilling. However, the high cost and complex process of these backfilling methods limit their wide application in mines. To save cost and simplify the operational procedure, better backfill materials should be used. Recently, superhigh-water materials with a water content of up to 97% have been used in many coalmines to fill gobs. Compared with traditional backfill materials, superhigh-water materials are cheaper and resource-saving. In addition, superhigh-water materials contain less inorganic salts and toxic metals in comparison with traditional cemented paste backfill, which can avoid secondary pollution. This material contains two principle components (Components A and B) and a small percentage of compound accelerators and composite retarders. Component A is composed of superretarding dispersant and bauxite. Component B mainly consists of gypsum and a compound accelerator. The two components are firstly mixed with water (more than 95% by weight) to form Grouts A and B. Then, these two grouts are mixed and filled in the gob.

Although the superhigh-water backfill mining method can effectively prevent rockburst hazard in the rib pillar, water may seep through this backfill material into the working face. Therefore, the width of the rib pillar should be large enough to prevent water seepage. The aim of this study is to design the width of rib pillar considering both rockburst and water-seepage prevention.

The remaining paper is organized as follows. Section 2 describes layout of longwall panels and the lithography of the overlying strata. Section 3 introduces overlying structural characteristics during gob-side longwall mining. In Section 4, the stress of the T-shaped structure will be analyzed. The method to design the width of the rib pillar and its field application are discussed in Section 5 and Section 6, respectively. Finally, conclusions and future work are summarized in Section 7.

2 SITE DETAILS

Yineng Coalmine (located in Shandong Province, China) adopted a fully mechanized longwall mining method to extract underground coal from coal seam 3. The designed production capacity is 600,000 tonnes per year. The gob was backfilled with superhigh-water backfill to control roof caving. The layout of longwall panel CG1307 (LW CG1307) adjacent to backfilled Gob CG1306 was influenced by the boundary of the mine field and faults, and shaped like a knife handle, as shown in Figure 1. The length of LW CG1307 was about 970 m, and its width varied from 39 to 80 m. The length of Gob CG1306 was similar to that of LW CG1307, and its width varied from 100 m to 130 m. The cover depth of coal seam 3 varied from 640 m to 700 m, and the coal seam with thickness varying from 2.5 to 3.7 m had an average inclination of 7°. From the laboratory test, the dynamic failure time of the coal is 115.2 ms, elastic energy index is 2.281, and the burst energy index is 2.164. A compression test shows the average uniaxial compressive strength of the coal seam is 12.5 MPa.
Figure 2 shows the stratigraphic column. It can be seen that both the immediate and main roofs are medium sandstones with thicknesses of 4.3 m and 4.4 m, respectively. The nearest fine sandstone subkey stratum is located 25.3 m from the coal seam with thickness of 11.2 m. The 14.2-m medium sandstone key stratum is situated 93.4 m from the coal seam.

### Table: Stratigraphic Column

| Lithology          | Legend | Thickness (m) | Height from coal seam (m) | Remark             |
|--------------------|--------|---------------|---------------------------|--------------------|
| Medium sandstone   |        | 14.2          | 93.5                      | Primary key stratum|
| Argillaceous sandstone group | | 45.1          | 48.4                      | Bedrock            |
| Coal seam 2        |        | 0.2           | 48.2                      |                    |
| Mudstone           |        | 3.5           | 44.7                      |                    |
| Medium sandstone   |        | 3.1           | 41.6                      |                    |
| Siltstone          |        | 5.1           | 36.5                      |                    |
| Fine sandstone     |        | 11.2          | 25.3                      | Sub key stratum    |
| Siltstone          |        | 3.9           | 21.4                      |                    |
| Sandy mudstone     |        | 6.7           | 14.7                      |                    |
| Mudstone           |        | 3.5           | 11.2                      |                    |
| Medium sandstone   |        | 4.4           | 6.8                       | Main roof          |
| Fine sandstone     |        | 2.5           | 4.3                       |                    |
| Medium sandstone   |        | 4.3           | 0.0                       | Immediate roof     |
| Coal seam 3        |        | 3.0           | --                        | Coal seam          |
| Mudstone           |        | 0.6           | --                        | Immediate floor    |
| Siltstone          |        | 3.8           | --                        | Main floor          |

3 | OVERLYING STRUCTURAL CHARACTERISTICS DURING GOB-SIDE LONGWALL MINING

According to the “Key Strata Theory” proposed by Qian,35,36 a key stratum is defined as a stratum that controls the movement of partial (subkey stratum) or whole (primary key...
stratum) overlying strata. When a primary key stratum fails, all the strata above it will subside, while only partial overlying strata subside when a subkey stratum is broken. There is only one primary key stratum in the overlying strata, but several subkey strata may exist (Figure 2). This section will further analyze the overlying structural characteristics based on the Key Strata Theory, pillar support effect, and backfill effect during gob-side longwall mining.

3.1 Limit equilibrium theory

The rib pillar between the backfilled longwall gob and longwall panel should (a) have high load-bearing capacity to avoid overall burst instability and (b) not be overall plastic, that is, an elastic area should exist in the pillar to prevent water seepage from the gob. Therefore, a large-width coal pillar is generally used in deep superhigh-water backfill stope. In this case, the formation of the overlying structure depends on two factors: plastic area width and load-bearing capacity of the rib pillar.

The width of the plastic area (ρ) in the rib pillar (Figure 3) can be determined by limit equilibrium theory:

\[ \rho = \frac{m\delta}{2\tan\Psi_0} \left[ k\gamma H + \frac{c_0}{\tan\Psi_0} + \frac{p_z}{\delta} \right] \]

where \( m \) is the thickness of the coal seam; \( \delta \) is coefficient of horizontal pressure; \( c_0 \) is cohesive force between coal seam and roof or floor; \( \Psi_0 \) is the internal friction angle of the coal seam; \( p_z \) is the resistance force exerted by the support system; \( k \) is the stress concentration coefficient; \( \gamma \) is the average bulk weight of the overlying strata; and \( H \) is the cover depth of the coal seam.

Generally, the plastic width of the coal pillar (D) ranges from 2 to 9 m. Therefore, when the pillar width exceeds 4-18 m (Figure 3), elastic area will appear in the pillar, which will influence the overlying strata structure. The discussion of the following section is based on the assumption that \( D > 2\rho \) and overall burst instability does not occur.

3.2 State of the primary key stratum above backfilled gob

After mining starts, the immediate roof will cave firstly and as the gob area increases, the strata above the immediate roof will fail one by one from bottom up and cave into the gob. In the overlying strata, the primary key stratum is relatively thick with higher strength and flexural rigidity, and thus remains stable during mining. There are two states of the primary key stratum. If there is enough movement space for the primary key stratum, it will separate from the lower strata (State 1). The movement space is related to several factors such as the thickness and strength of the primary key stratum, the distance from coal seam to the primary key stratum, as well as the backfilling effect, fracture degree, and bulking coefficient of lower strata. If the movement space is not large enough, the primary key stratum will touch the lower caved strata (state 2), as shown in Figure 4.

During mining, the primary key stratum may separate from the lower strata, the separation criterion can be defined as

\[ \frac{m}{h} \geq \frac{K - 1}{1 - \eta} \]

and when the following condition satisfies, the primary key stratum will touch the lower strata:

\[ \frac{m}{h} < \frac{K - 1}{1 - \eta} \]

where \( m \) is the thickness of the coal seam; \( h \) denotes the distance between the primary key stratum and the coal seam; \( \eta \) is the backfilling ratio of the gob; and \( K \) is the bulking coefficient of the strata from the coal seam floor to the primary key stratum floor.

For backfilled Gob CG 1306, \( m = 3.0 \) m, \( h = 25.3 \) m, \( \eta = 0.9, K = 1.3 \). Substituting the above values into Equation (2), we can obtain that \( m/h = 0.12 \) and \( (K - 1)/(1 - \eta) = 3 \), and hence \( m/h \ll (K - 1)(1 - \eta) \), indicating that the primary key stratum was in touch with the lower strata.
3.3 | T-shaped overlying strata structure

In the T-shaped overlying strata structure, the key stratum serves as the “skeleton” of the stratum system, supporting the overlying strata of the stope, and forming the horizontal structure of the T-shaped model. The horizontal structure is bent and deformed in the vertical direction. The superhigh-water backfill body in gobs at both sides of the rib pillar supports the caved and deformed strata, forming the clamped structure at both sides of the T-shaped structure, which bears loads from horizontal and vertical directions.

For a gob-side panel (Figure 5A), the overlying strata will fracture from bottom up with a fracture angle \( \alpha \). Assuming the widths of the two gobs are \( L_0 \) and \( l_0 \), respectively, and hanging lengths of the key stratum are \( L \) and \( l \), respectively, the following equations can be obtained:

\[
L = L_0 - 2h \cot \alpha \quad (4)
\]

\[
l = l_0 - 2h \cot \alpha \quad (5)
\]

The structure consisting of the primary key stratum, the rib pillar, and the overlying strata above the rib pillar is shaped like the letter “T” and thus is called T-shaped structure,\(^{40}\) as shown in Figure 5B. The key stratum (horizontal
support) supports the above overlying strata. The rib pillar together with its overlying strata (vertical support) supports the key stratum and isolates the gobs on both sides. This vertical support is compressed and deforms compatibly with the horizontal support in vertical direction. Assuming the thickness of the coal seam is \( m \); the distance between the key stratum and the coal seam is \( h \) and the thickness of the key stratum is \( h_1 \), the vertical height of the T-shaped support structure is \( m + h + h_1 \). The horizontal length is defined as the length between the two touch points above the two gobs, which is equal to \( D + 2h \cot \alpha + 0.5(L + l) \).

4 | STRESS ANALYSIS OF THE T-SHAPED SUPPORT STRUCTURE

4.1 | Construction of the mechanical model of the T-shaped support structure

The following assumptions are adopted to analyze the T-shaped support structure.

1. The length of the horizontal support (the length of the key stratum between the two touch points) is much larger than the width of the rib pillar.
2. The horizontal and vertical supports of the T-shaped structure are bent and compressed, respectively.
3. The rib pillar is simplified as an elastic hinged support.
4. The support forces applied to the key stratum by the rock mass above the rib pillar are simplified as concentrated forces \( F_s \), \( F_l \), and \( F_L \) respectively (Figure 6B,C).
5. The influence of dip angle of the coal seam on its abutment-stress distribution is non-negligible when the dip angle is larger than 8°. In this study, the dip angle of the coal seam is 7°, and therefore, the mathematical model is constructed without considering the influence of the dip angle of the coal seam.
6. The surface force between the key stratum and the gob can be simplified as concentrated force for calculation simplification with sufficient accuracy in engineering according to [2].

The horizontal force \( F_h \) applied to the key stratum can be given by

\[
F_h = \frac{h_1}{2} \int_\frac{L_0}{2}^{L_0 + D} \sigma' dx
\]

where \( \sigma' \) is the bending normal stress in the section (Figure 6A).

As the stress on both sides of the neutral plane is equal in magnitude and opposite in direction and, therefore, the horizontal force will not cause bending moment to the T-shaped structure.

\[ w_q \big|_{x = \frac{L_0 + D}{2}} = -\frac{q (L_0 + D) \left[ 8A^3 - 4A (L_0 + D)^2 + (L_0 + D)^3 \right]}{384EI} \]

\[ (7) \]

where \( E \) and \( I \) are the elastic modulus and cross-sectional moment of inertia, respectively.

2. When the model is subject to concentrated force \( F_s \) (Figure 7C), the deflection \( w_F \) of the stratum at \( x = 0.5(L_0 + D) \) is given by

\[
w_F \big|_{x = \frac{L_0 + D}{2}} = \frac{F_s (L_0 + D) \left[ 4A^2 - (L_0 + D)^2 - (L_0 + D)^3 \right]}{96AEI}
\]

\[ (8) \]
where $A$ is the length of the key stratum, $A = D + 0.5(L_0 + l_0)$.

3. Assuming the key stratum does not fail and ignoring its vertical compressive deformation, the compatibility equation is given by

$$w_q |_{x=\frac{L_0+l_0}{2}} + w_F |_{x=\frac{L_0+l_0}{2}} = 0$$

(9)

Substituting Equations (7) and (8) into Equation (9) gives

$$F_s = \frac{Aq \left[ 8A^3 - 4A(L_0 + D)^2 + (L_0 + D)^3 \right]}{4 (l_0 + D) \left[ 4A^2 - (L_0 + D)^2 - (l_0 + D)^2 \right]}$$

(10)

5 | DESIGN OF WIDTH OF RIB PILLARS BASED ON ROCKBURST AND WATER-SEEPA GE PREVENTION

Usually, in deep rockburst-prone mines, small rib pillars with width less than 9 m are adopted. However, the width of the rib pillar needs increasing to prevent water-seepage of the superhigh-water backfill body.

5.1 | Design of width of the rib pillar based on rockburst prevention

1. Abutment stress in the rib pillar

The rib pillar is subject to concentrated force $F_s$, and inverted trapezoidal rock weight, as shown in Figure 6C. The area of the inverted trapezoidal is

$$S = (hcot \alpha + D) h$$

(11)

The abutment stress applied to the rib pillar is calculated as

$$\sigma_c = \frac{F_s + \gamma S}{D} = \frac{F_s}{D} + \left( \frac{hcot \alpha}{D} + 1 \right) h$$

(12)

where $\gamma$ is the average bulk density of the overlying strata.

2. Load-bearing capacity of the rib pillar

The backfill body exerts lateral force to the lower part of the rib pillar (Figure 8). Therefore, the load-bearing capacity in the lower part of the rib pillar is higher than that in the upper part. Hence, the load-bearing capacity of the rib pillar is represented by the strength of its upper part, which is given by

$$R = \left( \frac{2\rho}{D} \varphi_{\text{min}} + \frac{D - 2\rho}{D} \varphi_{\text{max}} \right) \sigma_c$$

(13)

where $\sigma_c$ is the uniaxial compressive strength of the rib pillar; $\rho$ is the width of the plastic area; $D$ is the width of the rib pillar; and $\varphi$ is a compressive coefficient related to rock stress state. When $D > 2\rho$, elastic area exists in the rib pillar, and $\varphi_{\text{max}} = 3 - 5$ and $\varphi_{\text{min}} = 1$. When $D \leq 2\rho$, the whole rib pillar is plastic and $R \approx \sigma_c$.

3. Criterion for overall burst instability of the rib pillar

According to the strength criterion of rockbursts, rockburst of the coal pillar is directly related to its actual abutment stress and its load-bearing capacity. Therefore, we define the rockburst index by the ratio of the abutment stress to the load-bearing capacity of the coal pillar. Our group has applied this rockburst index in over 30 rockburst-prone mines in China. In rockburst-prone coal seams, the error can be
controlled within 10%, which satisfies the engineering requirements. Therefore, the rockburst criterion is defined as follows:

\[ I_C = \frac{\sigma_z}{R} \]  

(14)

where \( I_C \) is the rockburst index. In this study, we use the following values of \( I_C \) to define rockburst intensity (Table 1), as per recommendation by previous literature.11,43

According to the above definition, we can obtain different widths of the rib pillar under different stress states. The width of the rib pillar for rockburst prevention should be larger than the limit stability width of the rib pillar (\( D_c \)).

5.2 Design of width of the rib pillar based on water-seepage prevention

The width of the rib pillar should be larger than the width of the plastic area in the pillar to prevent water seepage. Considering gobs exist at both sides of the rib pillar, the width of the rib pillar should satisfy the following condition:

\[ D > 2\rho \]  

(15)

6 CASE STUDY

6.1 Determination of width of the rib pillar in Yineng Coalmine

In this case study, the values of the parameters are as follows: the thickness (\( h_1 \)) of the subkey stratum is 11.2 m; the distance (\( h \)) between the subkey stratum and coal seam 3 is 25.3 m; the distance (\( \Delta h \)) between subkey stratum and primary key stratum is 57 m; the average bulk density (\( \gamma \)) of the overlying strata is 25 kN/m³. Considering the above values of parameters, the load exerted on the subkey stratum by its overlying strata is \( q = \Delta h \gamma = 1.43 \) MPa. The widths of Gob CG 1307 and Gob CG 1306 are \( L_0 = 50 \) m and \( l_0 = 110 \) m, respectively; and fracture angle (\( \alpha \)) of the overlying strata is approximately 80°. Substituting these values into Equations (4) and (5), we can obtain that \( L = L_0 - 2h \cos \alpha = 41.2 \) m; \( l = l_0 - 2h \cos \alpha = 101.2 \) m. The length of the horizontal support of the T-shaped structure is \( A = D + 2h \cos \alpha + 0.5(L + l) = (D + 80) \) m. Coal seam 3 is 3 m in thickness with a compressive strength of 12.5 MPa. The plastic parameters are \( \varphi_{\max} = 3 \), \( \varphi_{\min} \approx 1 \), and \( \rho \approx 3 \) m. Substituting the above parameters into Equations (12)-(14), we can obtain the curves of \( \sigma_z \), \( R \), and \( I_C \) vs width of the rib pillar.

![Figure 9](image_url)  
**Figure 9** \( \sigma_z \), \( R \), and \( I_C \) vs width of the rib pillar

![Figure 10](image_url)  
**Figure 10** Distribution of microseismic events: (A) Plan view; (B) Cross-section view

| \( I_C \)       | Intensity |
|----------------|-----------|
| \( I_C < 1.0 \) | None      |
| \( 1.0 \leq I_C < 1.2 \) | Weak    |
| \( 1.2 \leq I_C < 1.5 \) | Moderate |
| \( 1.5 \leq I_C \) | Intense  |

| TABLE 1 | Relationship between IC and rockburst intensity |

The distance (\( h \)) between the subkey stratum and coal seam 3 is 25.3 m; the distance (\( \Delta h \)) between subkey stratum and primary key stratum is 57 m; the average bulk density (\( \gamma \)) of the overlying strata is 25 kN/m³. Considering the above values of parameters, the load exerted on the subkey stratum by its overlying strata is \( q = \Delta h \gamma = 1.43 \) MPa. The widths of Gob CG 1307 and Gob CG 1306 are \( L_0 = 50 \) m and \( l_0 = 110 \) m, respectively; and fracture angle (\( \alpha \)) of the overlying strata is approximately 80°. Substituting these values into Equations (4) and (5), we can obtain that \( L = L_0 - 2h \cos \alpha = 41.2 \) m; \( l = l_0 - 2h \cos \alpha = 101.2 \) m. The length of the horizontal support of the T-shaped structure is \( A = D + 2h \cos \alpha + 0.5(L + l) = (D + 80) \) m. Coal seam 3 is 3 m in thickness with a compressive strength of 12.5 MPa. The plastic parameters are \( \varphi_{\max} = 3 \), \( \varphi_{\min} \approx 1 \), and \( \rho \approx 3 \) m. Substituting the above parameters into Equations (12)-(14), we can obtain the curves of \( \sigma_z \), \( R \), and \( I_C \) vs width of the rib pillar.

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**Figure 10** Distribution of microseismic events: (A) Plan view; (B) Cross-section view
and $I_C$ as a function of $D$, as shown in Figure 9. It can be seen that when $D \leq 9$ m, $I_C > 1.0$, suggesting weak rockburst risk, while when $9$ m $< D \leq 13.5$ m, $0.5 \leq I_C < 1.0$, indicating no rockburst risk, and $I_C$ decreases with increasing $D$. Therefore, $D_C$ should vary between 9 m and 13.5 m based on rockburst prevention. Considering the undetermined factors during mining and tunneling, $D_C$ should vary between 9 m and 10 m.

From the perspective of water-seepage prevention, $D > D_S \geq 2 \rho = 6$ m. Considering both water-seepage prevention and rockburst prevention, the width of the rib pillar should meet the following condition: $D \geq \max [D_C, D_S] = 10$ m.

### 6.2 Field application

The width of the rib pillar between CG 1306 and CG 1307 is 10 m. During mining, microseismic monitoring system was deployed to monitor movement of strata and stability of the coal pillar. Figure 10 shows the distribution of microseismic events from start line to the position where the gob behind the working face is square (58 m from the start line). It can be seen from Figure 10A that the influential range of the microseismic events in front of the working face is 65 m. Both lateral influential ranges are 30 m. Behind the working face, the largest influential range of microseismic events is 25 m. From Figure 10B, it can be observed that the largest movement range of the overlying strata is 50 m (0-30 m for lower strata and 30-50 m for upper strata). There is no microseismic event with energy larger than $10^5$ J and the total daily microseismic energy is comparatively small (less than $10^6$ J), suggesting there is no large-scale rock movement and fracture caused by instability of the rib pillar. From the distribution of the microseismic events, it can be inferred that the subkey stratum separated, bended and then was in touch with the lower strata, while the primary key stratum was stable without movement.

In addition, the rockburst risk was determined by examining borehole drill cuttings according to the following equations:

$$G = \pi r^2 \omega \rho$$

where $G$ is the critical amount of the borehole drill cuttings; $r$ is the radius of the borehole (0.021 m in this study); $\rho$ is the average bulk density of the coal seam ($1.37 \times 10^3$ kg/m); and $\omega$ is the borehole drill cuttings ratio which is the ratio of the borehole depth to coal seam thickness. Figure 11 shows the amount of borehole drill cuttings vs borehole depth. It can be seen that all the actual amounts of borehole drill cuttings are smaller than the critical amounts of borehole drill cuttings, indicating that the rockburst risk of the rib pillar is very low.

The roadway wall in front of the working face and the backfill body behind the working face is shown in Figure 12. No spalling or water seepage is observed, indicating that the purpose of rockburst and water-seepage prevention is achieved with 10-m rib pillar.

![FIGURE 11 Amount of borehole drill cuttings vs borehole depth](image1)

![FIGURE 12 Roadway wall located at 65 m in front of the working face (A) and filling body at 5 m in the gob behind the working face](image2)
7 | CONCLUSIONS

This paper designs the width of the rib coal pillar in long-wall mining considering both rockburst and water-seepage prevention. The following conclusions can be drawn from the paper.

1. The width of the rib coal pillar is critical to the formation of overlying strata structure which determines the overall burst instability of the rib pillar. In addition, designing the width of the rib pillar should ensure the rib pillar is partially elastic to prevent water seepage.

2. The key stratum, the rib pillar, and the overlying strata above the rib pillar form a T-shaped support structure. The mechanical model of the T-shaped structure is established by taking the key stratum as elastic rock beam and the rib pillar as a hinged support. The criteria for overall burst instability are proposed according to the established mechanic model.

3. Based on the proposed width design method, a 10-m rib pillar in Yineng Coalmine was designed. From the analysis of the microseismic monitoring results and borehole drill cuttings during mining, the rib pillar was stable without water seepage, indicating the width design method proposed in this study is effective.

The proposed method is only verified in Yineng Coalmine with an approximately horizontal coal seam. In the future work, this model for prevention of rockburst and water seepage should be slightly modified for application in coal seams with large dip angles. In addition, other preventive measures such as reducing working face advancing speed, selecting appropriate extraction methods and sequences, and strategically placing supports should also be taken into account.

ACKNOWLEDGMENTS

This work is supported by Anhui Natural Science Foundation (Grant No. 1908085QE186), State Key Laboratory of Mining Response and Disaster Prevention and Control in Deep Coal Mines (Anhui University of Science and Technology) (Grant No. SKLMRDPC19ZZ03), Young Teachers Scientific Research of Anhui University of Science and Technology (Grant No. QN2018110), and Henan Key Laboratory for Green and Efficient Mining & Comprehensive Utilization of Mineral Resources (Grant No. KCF201808).

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How to cite this article: Zhang M, Zhang J, Jiang F, Jiao Z. Design of rib pillars in deep longwall mines based on rockburst and water-seepage prevention. *Energy Sci Eng*. 2021;9:256–266. https://doi.org/10.1002/ese3.845