ABSTRACT
The variation of hard roof thickness is an essential contributor in triggering rock bursts during longwall mining. Case analysis and numerical modeling were used to study the stress and energy characteristics of the coal and rock mass and its fracture behaviour in the roof thickness variation zone (RTVZ). The results show that the coal seam has higher initial stress if overlain by a thicker hard roof, whose stress monitoring value is 1.8–2.6 times that of the thin zone. The increasing variation in the roof thickness or the roof properties causes a greater initial stress change in the coal seam. In the thick roof zones, the superposition of the advanced abutment pressure and the increased initial stress will result in a high-stress concentration area, where the stress mutation coefficient value can be up to 1.08–1.15. A higher rock burst risk might thus present in the roadway near the longwall in the thick roof zone, where more intensive elastic energy was released in the coal/rock mass. Also, it is more likely to have a significant dynamic load in the thin roof zone due to the higher possibility of roof breakage, and the total microseismic energy can reach 1.8–3.2E+08J.

HIGHLIGHTS
• Case analysis and numerical modelling were used to study the formation mechanism of stress anomaly in coal seams, energy evolution characteristics of the coal/rock mass and its fracture behaviour in the RTVZ.
• The mechanism of rock bursts induced by coal mining in the RTVZ is determined. The thick roof zone has high-stress concentration, where more intensive elastic energy is released in the coal/rock mass. Due to easier roof breakage, it is more likely to have a significant dynamic load in the thin roof zone.
• The prevention and control method of rock bursts in the RTVZ is put forward. The rock bursts can be relieved by reducing the initial stress increased in the thick roof zone. Strengthening roadway support can reduce the influence of dynamic load on the roadway.

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1. Introduction

As a special dynamic phenomenon in coal mining, rock bursts are mainly induced by substantial local stress concentration resulting from mining activities, which severely affects underground mining safety and productivity (Cao et al. 2015; Vižintin et al. 2016; Zhao et al. 2018; Guo et al. 2019; Dou et al. 2021). Two fundamental factors account for rock bursts: the initial stress before mining and the redistribution of stress during mining (Pan and Meng 2004; Orlecka-Sikora et al. 2012; Guo et al. 2017). Stress anomaly concentration areas (faults, folds, coal pillars, etc.) are more vulnerable to rock bursts. For example, the particular roof structure near the faults, which may prevent abutment pressure from transferring to the deeper rock mass, can lead to stress concentration (Cai et al. 2021; Cao et al. 2021). Fold-induced rock bursts mainly occur when the static stress is concentrated, while the static stress is mostly horizontal (Wang et al. 2018; Guo et al. 2022). Rock bursts around pillars are mainly caused by concentrated static stress (mainly vertical stress; Cao et al. 2016).

Moreover, stress anomaly concentration of coal seams usually happens in the tectonic areas with facies change (TAFC). Based on in-situ stress measurement and mine pressure observation, Sun (2003) found that tectonic stress anomalies would occur in local areas where the thickness of coal seam changed. Álvarez-Fernández et al. (2009) used numerical models to analyze the specific case of a coal seam mined by the sublevel caving method. It is found that stress and deformation in certain advanced headings significantly increased due to thinning of the coal seam. Through field observation and numerical analysis, Zhu et al. (2016) studied the influence of local variations in the thickness of a coal seam on in-situ stress and surrounding stress, and the results show that overstress correlated with the degree of variation in coal seam thickness. Zhao et al. (2016) investigated the influence of variations in the thickness of a coal seam on the advanced abutment pressure and energy evolution. They revealed the mechanical mechanism of rock bursts in the coal thickness varying zone. Guo et al. (2019) analyzed several rock bursts happened in TAFC in detail and discovered that coal seam thickness, dip angle, and coal quality affected rock bursts. The superposition of high in situ stress and roadway abutment pressure in TAFC leads to high stress concentration.

The above studies have indicated that the TAFC may contribute to the increasing number of rock bursts, and these changes may be tectonic (small faults or folds) or sedimentary (thickening and thinning) in origin (Zhai et al. 2016; Guo et al. 2019). However, facies change can manifest in variation in coal seam thickness (VCST) or variation in roof thickness (VRT). Local stress concentration in the thickness varying zone is the essential reason for rock bursts induced by the VCST and VRT (Guo et al. 2017). In comparison, VRT, which can only be obtained from boreholes, is less obvious than VCST as the latter can be directly shown in the advancement of the working face. Therefore, rock bursts induced by variation in hard roof thickness haven’t fully attracted researchers’ attention.

Ordos Basin has unique sedimentary characteristics. For example, its roof usually contains one single stratum not only of great thickness but of greatly varying thickness (Chen et al. 1995; Zhao et al. 2020). In this case study, the roadway had suffered significant damages, such as side bulge, roof subsidence, and floor bulge. At the same
time, according to the borehole analysis, the thickness of the overlying key stratum exhibited apparent variation, giving rise to what is known as "thickening".

In this article, the rock bursts cases in TAFC is analyzed first, with their conditions introduced and investigated in detail. Subsequently, the formation mechanism of tectonic stress in the hard roof thickness variation zone (RTVZ) is analyzed with elastic mechanics theory. Then, FLAC$^{3D}$ simulation is used to investigate the stress distribution characteristics, energy evolution, and roof fracture law near the working face (Itasca 2012). Finally, the rock burst mechanism induced by coal mining in RTVZ is further explored.

2. Rock bursts cases induced by VRT

2.1. Case of longwall mining from thin roof zone to thick roof zone

Yitai Coal Mine is located in Ejin Horo Banner, Ordos Basin, of which LW103 is the second mining face. The LW103 has solid coal and 101 goaf on either side, and there are two coal pillars with a width of 30 m between the LW103 and 101 goaf. The LW103 has a strike length of 2480 m and a width of 210 m and mainly mines 3-1 coal seam. The average burial depth, the thickness and the dip angle are 706.3 m, 6.7 m, and $1^{\circ} - 3^{\circ}$, respectively. The dip angle indicates that it is nearly a horizontal coal seam.

The physical and mechanical parameters of Yitai Mine are tested in Table 1. The physical and mechanical properties of fine sandstone and medium sandstone are similar, but sandy mudstone is comparatively weaker than the sandstone stratum. The discriminant equation for the stratum $n$ as the key stratum is (Guo et al. 2021):

$$ (q_n)_m < (q_{n-1})_m $$

Where $(q_n)_m$ is the load of stratum $n$ on the stratum $m$, which satisfies the following relationship:

$$ (q_n)_m = E_m h_m^3 \sum_{i=m}^{n} \gamma_i h_i / \sum_{i=m}^{n} \gamma_i h_i^3 $$

Where $m$, $n$, $i$ are the serial numbers of roof strata; $E_m$ and $h_m$ are the elastic modulus and thickness of the stratum $m$, respectively. $E_i$, $H_i$ and $\gamma_i$ are the elastic modulus, thickness and bulk density of the stratum $i$, respectively.

Table 1. Actual measured parameters of coal and rock mechanics in Yitai Coal Mine.

| Lithology         | Uniaxial compressive strength (MPa) | Tensile (MPa) | Elasticity modulus (GPa) | Poisson | Density (kg/m$^3$) |
|-------------------|-------------------------------------|--------------|--------------------------|---------|-------------------|
| Powder sandstone  | 24.88                               | 3.91         | 7.23                     | 0.13    | 2357              |
| Fine sandstone    | 22.77                               | 3.67         | 6.32                     | 0.13    | 2303              |
| Medium sandstone  | 22.57                               | 3.81         | 6.24                     | 0.13    | 2310              |
| Pebby sandstone   | 16.82                               | 1.92         | 1.82                     | 0.12    | 2380              |
| Sandy mudstone    | 16.70                               | 2.70         | 3.13                     | 0.15    | 2018              |
| Coal              | 14.54                               | 0.83         | 2.66                     | 0.18    | 1386              |
Whether the roof strata are the key strata is determined by the properties and thickness of them. The larger the elastic modulus and thickness of the roof, the more likely it is to be the key stratum. Bending, cantilever, fracture and slip of key stratum affect the accumulation and release of elastic energy of roof, which has great influence on the rock bursts (Xiaojun et al. 2011).

According to the boreholes samples near the LW103, it is found that there is a thick roof stratum of medium-fine sandstone in the area of nearly 200 m above coal seam 3-1, which is located at about 20 m above the coal seam and varies greatly in thickness (ranging from 60 to 110 m). The calculation of key stratum indicates that it is the key stratum of the LW103, which is responsible for the rock bursts in the area. With the advancement of LW103, the roof changes from thin to thick. Then the contour map of the variation in the sandstone roof thickness is shown in Figure 1(a).

Since the mining of LW103 in March 2018, dynamic manifestation of various degrees had appeared frequently in the goaf-side roadway, resulting in multiple tunnel failures and equipment damage, such as floor cracking, floor heave, and local deformation of the sidewall. The microseismic monitoring system was installed, and the stress monitoring devices were placed in the mining wall of the goaf-side roadway for every 30 m. The damage zone and location of large energy microseismic events (energy > $10^4$J) during the mining of LW103 are shown in Figure 1(b), and the pressure failure situation and characteristics of the roadway are shown in Figure 1(c).

During a safety inspection of the LW103, several significant stress increases were observed. Figure 2(a) depicts the relationship between the monitored stress values and VRT when there is no mining disturbance. Figure 2(b) shows the relationship between microseismic data and VRT during the mining of LW103, when the total microseismic frequency and total energy are summarized every 10 m. In Figure 2, the LW103 advances from thin roof zone to thick roof zone, and the thickness of the roof increases gradually from 78 to 107 m. In addition, the shaded part in the figure signifies the upper and lower limit envelope range. In thin roof zone, the readings of the shallow hole and deep hole stress gauge are low (4.56 and 4.63 MPa in average, respectively), while, in thick roof zone, the stress monitoring values are higher (11.09 and 11.93 MPa in average, respectively). The relationship between the microseismic frequency and VRT is similar to the change in stress value. In thin roof zone, the microseismic frequency is less (130 times in average), and in contrast, the microseismic frequency in thick roof zone is higher (283 times in average). However, the maximum value of microseismic energy appears in thin roof area, and the total microseismic energy is $1.9E+08$J.

2.2. Case of longwall mining from thick roof zone to thin roof zone

Menkeqing Coal Mine is located in Wushen Banner (south of Ejin Horo Banner), Ordos Basin, of which LW3102 is the second mining face mainly mining coal seam 3-1. Solid coal and goaf 3101 are on both sides of LW3102. There is a coal pillar with a width of 35 m between LW3102 and goaf 3101. LW3102 has a strike length and a dip width of 5540 and 300 m, respectively. The burial depth of the coal seam is 690–700 m, the thickness is 4.35–5.47m, and the dip angle is 1°–4° (almost horizontal).
The physical and mechanical parameters of Menkeqing Coal Mine (Table 2) indicate that the physical and mechanical properties of powder sandstone, fine sandstone, and medium sandstone are stronger than those of sandy mudstone. According to the borehole

![Figure 1](image_url)

(a) Contour map of medium-fine sand roof thickness in LW103 of Yitai Mine. (b) The damage zone and location of large energy microseismic events (energy >10^4J). (c) Roadway conditions after rock bursts occurring in RTVZ.

The physical and mechanical parameters of Menkeqing Coal Mine (Table 2) indicate that the physical and mechanical properties of powder sandstone, fine sandstone, and medium sandstone are stronger than those of sandy mudstone. According to the borehole
samples around LW3102, a layer of medium sandstone with great variation in thickness exists in 200 m above the coal seam 3-1. The roof is approximately 30 m above the coal seam, and the layer thickness is between 20 and 60 m. According to the calculation of key stratum, this is the key stratum of the LW3102, which is responsible for the rock bursts in the area. With the advance of the LW 3102, the roof becomes thinner. The contour map of the variation of the sandstone roof thickness is shown in Figure 3(a).

Since the mining of LW3102 in August 2017, there appeared different degrees of dynamic manifestation in the goaf-side roadway, such as side bulge, roof subsidence, floor drum, single damage, etc. During the mining of LW 3102, the microseismic monitoring system was arranged and the stress monitoring devices were placed on the mining wall of the roadway side for each 20 m. The damage zone and location of large microseismic events (energy $>10^3$ J) are shown in Figure 3(b), and the roadway conditions after rock bursts occurring are shown in Figure 3(c).
A significant increase in stress levels was observed in LW3102. Figure 4(a) depicts the relationship between the monitored stress values and the VRT, when there is no mining disturbance. Figure 4(b) showed the relationship between microseismic data and VRT during the mining of LW103. The LW3102 advances from thick roof zone to thin roof zone, and the thickness of the roof gradually decreases from 59 to 28 m. The shaded part is the upper and lower limits of the envelope range. In the thick roof zone, the readings of the shallow hole and deep hole stress gauge are both large (11.74 and 12.10 MPa in average, respectively), while, in the thin roof zone, the stress monitoring value is lower (5.65 and 6.47 MPa in average, respectively). In the thick roof zone, there are more microseismic events (102 times in average), but in the thin roof zone, the microseismic frequency is much less (8 times in average). However, the maximum microseismic energy occurs in the thin roof zone, and the total microseismic energy is $3.2 \times 10^8$ J.

The above two cases have proved an apparent positive correlation between the stress values in the roadway and the VRT in the case of no mining disturbance. The static load stress is large in the thick roof zone, shown as an obvious stress-increasing area. The stress monitoring value in thick roof zone is 1.8–2.6 times that in thin roof zone. The microseismic frequency is higher in the thick roof zone; however, the total microseismic energy has a maximum value in the thin roof zone.

In general, high-stress zones are prone to induce microseismic events, and thus considered as rock burst-prone zones (Jiang et al. 2006). Based on this analysis, theoretical analysis and numerical simulation will be combined to explain the formation mechanism of coal seam stress anomaly in the RTVZ, which will enrich the study on mechanism of rock bursts in TAFC and provide guidance for the monitoring and prevention of rock bursts.

### 3. Formation mechanism of stress anomaly of coal seam

#### 3.1. Theoretical analysis of stress anomaly of coal seam

Under the initial stress condition, the coal seam, roof, and floor are not affected by mining disturbance. The coal/rock mass does not exceed its elastic range, so RTVZ can be simplified as roof $a$ and roof $b$ (Zhao et al. 2016). Its overall mechanical properties are represented by the two elastic elements in series and in parallel (Figure 5).

In RTVZ, the elastic modulus in zone $a$, zone $b$, and zone $c$ is composed of roof $h$ and roof $s$ combined in series, with its equivalent elastic modulus $E$ represented as:

$$E = \frac{H \cdot E_{Rh} \cdot E_{Rs}}{H_s \cdot E_{Rh} + H_h \cdot E_{Rs}}$$

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**Table 2. Actual measured parameters of coal and rock mechanics in a mine of China Coal Mine.**

| Lithology         | Uniaxial compressive strength (MPa) | Tensile (MPa) | Elasticity modulus (GPa) | Poisson | Density (kg/m³) |
|-------------------|-------------------------------------|---------------|--------------------------|---------|-----------------|
| Powder sandstone  | 32.20                               | 5.50          | 8.23                     | 0.28    | 2426            |
| Fine sandstone    | 39.32                               | 4.40          | 7.12                     | 0.20    | 2450            |
| Medium sandstone  | 35.44                               | 4.23          | 6.90                     | 0.20    | 2488            |
| Sandy mudstone    | 21.40                               | 2.56          | 3.53                     | 0.28    | 2216            |
| Coal              | 16.01                               | 1.23          | 3.04                     | 0.32    | 1369            |
Figure 3. (a) Contour map of medium-fine sand roof thickness in LW 3102 of Menkeqing Coal Mine. (b) The damage zone and location of large energy microseismic events (energy $>10^3$J). (c) Roadway conditions after rock bursts occurring in RTVZ.
Where $H_h$ and $H_s$ are the thickness of roof $h$ and roof $s$ (m); $E_{Rh}$ and $E_{Rs}$ are the elastic modulus of roof $h$ and roof $s$ (MPa), respectively.

According to the stress-strain relationship of coal and rock:

$$
\sigma = E \cdot \varepsilon
$$

(4)

In this model, zone $a$, zone $b$, and zone $c$ are in parallel, so the strains ($\varepsilon_a$, $\varepsilon_b$, $\varepsilon_c$) are equal. Similarly, the stresses in each zone, as they are in series, are also the same. With Equations (3) and (4), the stress relationship in RTVZ can be obtained :

$$
\frac{\sigma_a}{\sigma_c} = \frac{E_a}{E_c} = \frac{H_{sc} \cdot E_{Rh} + H_{hc} \cdot E_{Rs}}{H_{sa} \cdot E_{Rh} + H_{ha} \cdot E_{Rs}}
$$

(5)

Where $\sigma_a$ and $\sigma_c$ are the stresses in zone $a$ and zone $c$ (MPa), $H_{ha}$ and $H_{ha}$ are the thicknesses of roof $h$ and roof $s$ in zone $a$ (m), $H_{hc}$ and $H_{sc}$ are the thicknesses of roof $h$ and roof $s$ in zone $c$ (m).
In order to qualitatively analyze the stress distribution in RTVZ, it is assumed that the thickness $H_{ha}$ and $H_{sa}$ of roof $h$ and roof $s$ in zone $a$ remain unchanged, and Equation (5) is simplified as a function of $ER_s/ER_h$ and $H_{hc}/H_{ha}$:

$$
\frac{\sigma_a}{\sigma_c} = \frac{H}{H_{ha}} - \frac{H_{hc}}{H_{ha}} \left(1 - \frac{ER_s}{ER_h}\right) \left[\frac{H}{H_{ha}} - \left(1 - \frac{ER_s}{ER_h}\right)\right]^{-1} \left(1 - \frac{ER_s}{ER_h}\right) \left(1 - \frac{ER_s}{ER_h}\right)
$$  

As hard roof $ER_h > ER_s$, when $H_{ha}$ in zone $a$ is thicker than $H_{hc}$ in zone $c$, $\sigma_a$ in zone $a$ is greater than $\sigma_c$ in zone $c$. In other words, the stress in the thickening zone is greater than that in the thinning zone. Figure 6(a) shows the relationship between stress ratio and roof thickness under certain roof properties. When $ER_s/ER_h$ remains constant, $\sigma_a/\sigma_c$ decreases linearly with the increasing of $H_{hc}/H_{ha}$ ($H_{ha}$ is fixed). Figure 6(b) shows that the relationship between stress ratio and elastic modulus ratio of the roof thickness is constant. When $H_{hc}/H_{ha}$ is constant, $\sigma_a/\sigma_c$ negatively correlates with $ER_h/ER_s$. It can be concluded that the greater the difference of properties or thickness of two roofs in RTVZ, the greater the variation of stress.

### 3.2. Numerical simulation of stress anomaly of coal seam

To study the influence of variation of hard roof thickness and roof properties on stress distribution, a numerical model of coal seam and its surrounding strata in RTVZ was established in FLAC$^3$d by referring to the thickness and property change of the basic roof. The size of the model is $300 \times 400 \times 150$ m, and the RTVZ is within $100$ m in the middle of the Y-axis. Other parameters are shown in Figure 7.

The elastic model is adopted to represent the constitutive model because the coal/rock mass is considered in a linear elastic state under initial stress (Cao et al. 2020). The parameters of the model are simplified based on the actual mechanical parameters of a mine (Itasca 2012; Arad et al. 2016; Li and Du 2016), as shown in Table 3. The simulation schemes are divided into two types: Scheme $a$: simulate the influence of VRT on initial stress distribution of coal seam ($ER_h=6.0$ GPa, $ER_s=3.0$ GPa, $H_{ha}=60$m, and $H_{hc}=10, 20, 30, 40,$ and 50 m, respectively); Scheme $b$: simulating the influence of roof properties on initial stress distribution of the coal seam ($H_{hc}=30$m,
Table 3. The roof properties and thickness. ($H_{ha}$=60m, $E_{Rs}$=3.0 GPa, and $E_{Rh}$=4.5, 6.0, 7.5, 9.0, and 10.5 GPa, respectively). It is worth noting that the other values in Table 3 follow the developing trend of roof properties and thickness but not the exact values in actual situations.

The load on the top of the key stratum can be simplified as a uniform load based on the key stratum control theory (Xu et al. 2001; Xie and Xu 2017). A uniform load of 15 MPa is applied on the top of the model to simulate a coal seam with a burial depth of about 700 m, and the gravity acceleration is 10 m/s$^2$. The horizontal displacements and the vertical displacements at the model’s bottom are fixed; X and Y directions are fixed boundaries.

According to the in-situ measured data of stress in the coal mine, the maximum principal stress is 17.55–32.42 MPa, and the direction is N ~ NNE. The intermediate principal stress, the minimum principal stress and the vertical principal stress are 13.93–19.82 MPa, 12.08–17.39 MPa, and approximately 18.20 MPa, respectively. The coal mine is dominated by horizontal stress. The maximum horizontal principal stress is about 1.5 times the vertical principal stress, and the minimum principal stress is

Figure 6. (a) Relationship between the stress ratio and roof thickness variation. (b) Relationship between the stress ratio and the elastic modulus ratio of the roof.
equal to the vertical principal stress. Therefore, horizontal gradient stress is applied in X and Y directions, and the stress coefficients in X and Y are set as 1.0 and 1.5, respectively. The boundary and initial conditions are then applied to the model to reach an initial equilibrium state.

Figure 8 shows the cloud map of stress distribution in RTVZ under initial stress state and the initial stress distribution under different simulation schemes. The initial stress varies greatly in RTVZ, when the roof thickness varies from thin to thick: it firstly decreases from the uniform state, then increased with the thickness of the roof, and reaches the maximum value in thick roof zone; when the roof thickness is stable, the initial stress returns to a uniform state and the maximum stress increases with the gradient of roof thickness (Figure 8(a)). The initial stress distribution caused by the variation of roof properties was similar to the VRT. The maximum stress increases with the rising of roof elastic modulus ratio (Figure 8(b)).

This model simulates that the burial depth of the coal seam is 710 m, and the thickness of roof strata above the coal seam is 110 m, so the vertical load on the top boundary is 15 MPa (0.025MN/m$^3$ * 600 m; 0.025MN/m$^3$ is the unit weight of the overlying strata; 600 m is the depth of the top boundary). The pre-mining stresses of the longwall model are influenced by the elastic modulus of each layer (Wei et al. 2020). Therefore, the influence of the hard roof properties and VRT on the initial stress is operationalized as the ratio of $\sigma_{uv}/\sigma_{c}$ (i.e., the ratio between each stress value minus the uniform load (a uniform load of 15 MPa is applied on the top of the model); Figure 9). In scheme a, when $E_{Rc}/E_{Rh}$ is fixed, the roof thickness $H_{hc}/H_{ha}$

Table 3. Model parameters used in the initial model.

| Model parameters       | Unit | Fine mudstone | Medium mudstone | Sandy mudstone | Coal |
|------------------------|------|---------------|-----------------|---------------|------|
| Density $\rho$         | Kg/m$^3$ | 2400          | 2300            | 2000          | 1400 |
| Elasticity modulus $E$ | GPa  | 8             | 6               | 3             | 1    |
| Poisson $v$            |      | 0.13          | 0.13            | 0.15          | 0.20 |
| Bulk modulus $K$       | GPa  |               |                 |               |      |
| Shear modulus $G$      | GPa  |               |                 |               |      |

Figure 7. Stratum structure and geometric model of RTVZ.

Table 3. Model parameters used in the initial model.
increases from 10/60 to 50/60, and the ratio of stress change decreases linearly from 2.29 to 1.27, which indicates that when the roof properties are constant, the greater the VRT, the greater the change of initial stress value. In scheme b, when $H_{hc}/H_{ha}$ remains unchanged, $E_{Rc}/E_{Rh}$ increases from 3.0/4.5 to 3.0/10.5, and the ratio of stress shows an inverse proportional trend (dropping from 1.91 to 1.26). It is shown that the greater the difference in elastic modulus of the roof, the greater the stress change gradient in the coal seam, which is consistent with the theoretical analysis from Equation (6).

4. Numerical simulation of coal seam mining

4.1. Construction of coal seam mining model

When the stress of coal/rock mass moves beyond its peak value and enter the post-peak stage of the stress–strain curve, the strain-softening model can reflect the post-
peak failure stage of coal/rock mass (Akdag et al. 2021; Xie et al. 2021). Zhou et al. (2022) simulated the deformation, damage and fracturing of rocks, and found that when the maximum tensile stress criterion is met for a given element, the element is damaged and weakened. The development of rock cracks is related to the cohesion and the angle of internal friction (Zhou et al. 2020; Yu et al. 2021). According to Martin and Chandler (1994), when the internal fracture of a rock mass started to expand under the action of stress, the cohesion was bound to decrease on the premise that the failure strength of rock mass remained unchanged. Hajiabdolmajid et al. (2002) derived the cohesion weakening and friction strengthening Equation on this basis, and its bonding strength was:

$$f(C, \Delta \varepsilon) = \begin{cases} 
C_i & (\Delta \varepsilon = 0) \\
(C_r - C_i) \cdot \Delta \varepsilon / \varepsilon_c & (0 < \Delta \varepsilon < \varepsilon_c) \\
C_r & (\Delta \varepsilon \leq \varepsilon_c) 
\end{cases}$$

(7)

The softening coefficient of friction $\phi$ can be expressed as:

$$f(\phi, \Delta \varepsilon) = \begin{cases} 
\phi_i & (\Delta \varepsilon = 0) \\
(\phi_r - \phi_i) \cdot \Delta \varepsilon / \varepsilon_c & (0 < \Delta \varepsilon < \varepsilon_c) \\
\phi_r & (\Delta \varepsilon \leq \varepsilon_c) 
\end{cases}$$

(8)

Where $C_i$ is the initial cohesion (Pa); $C_r$ is the residual cohesion (Pa); $\phi_i$ is the initial friction Angle ($^\circ$); $\phi_r$ is the residual internal friction Angle ($^\circ$); $\Delta \varepsilon$ is the equivalent plastic strain; $\varepsilon$ is the principal plastic strain.

The model of coal/rock mass in the process of longwall mining is set as the strain-softening model. The physical-mechanical parameters of coal/rock mass (Table 4) are
obtained from several trials based on mechanical tests and literature review (Itasca 2012; Wang et al. 2019). Other model parameters are shown in Table 3.

In order to study the influence of VRT on longwall mining, the VRT model ($H_{hc}=1/2 \times H_{ha}=30m$) was adopted. The mining method includes scheme a (pushing from thick roof zone to thin roof zone) and scheme b (pushing from thin roof zone to thick roof zone; Figure 10). Boundary coal pillars with a width of 50 m were set on both sides of the longwall to eliminate the influence of the boundary on mining (Cao et al. 2021). In addition, the model was rebalanced for every 20 m after excavation of the longwall.

4.2. Mining stress distribution in RTVZ

In the process of longwall mining, the stress in coal/rock mass is redistributed, and the stress concentration area is formed around the goaf. Rezaei et al. (2015c) and Rezaei et al. (2015a) used strain energy method to determinate longwall mining-induced stress concentration coefficient, which was about 1.6–1.8. But, when the longwall was affected by special geological structure, the mining stress concentration coefficient would increase again. Wei et al. (2021) revealed that when the longwall mining reached the influenced area of faults, the peak abutment stress increased from approximately 45 to 53.4 MPa, and the concentration coefficient of mining stress increased by 0.38. Chen et al. (2011) studied the influence of folding structure on the longwall mining. The post-mining stress concentration coefficient increased by about 0.5 in the synclinal structure zone. Álvarez-Fernández et al. (2009) studied the influence of TAFC on stress concentration coefficient after the longwall mining. When the coal thickness within 3 m gradually decreased from 3 to 1 m, the concentration coefficient of mining stress caused by coal mining increased by 2–3 times when the thickness remained unchanged. Zhu et al. (2016) studied that when the coal thickness within 10 m was thinning from 5 to 1 m, the mining stress concentration coefficient increased by 0.5–0.67. Guo et al. (2019) studied that when the thickness of coal seam within 10 m gradually thinned from 5 to 2 m, the stress concentration coefficient of the TAFC increased by 0.39–0.89 in the process of longwall mining.

In order to study the influence of the RTVZ on the mining stress of longwall, a monitoring line was arranged in the middle of the coal seam (at $X=150$ m and $Z=37$ m), and then the advanced abutment pressure was compared under the following three mining conditions: (1) mining from thin roof zone to thick roof zone, (2) mining from thick roof zone to thin roof zone and (3) mining through zone with roof of the same thickness (lithology of the roof is medium sandstone).

| Plastic strain | Cohesion (MPa) | Friction (°) | Cohesion (MPa) | Friction (°) | Cohesion (MPa) | Friction (°) | Cohesion (MPa) | Friction (°) |
|----------------|---------------|-------------|---------------|-------------|---------------|-------------|---------------|-------------|
| 0              | 10.00         | 36          | 8.00          | 32          | 5.00          | 28          | 3.00          | 25          |
| $1 \times 10^{-4}$ | 6.00         | 32          | 5.00          | 28          | 3.00          | 24          | 2.00          | 22          |
| $2 \times 10^{-4}$ | 4.00         | 28          | 3.00          | 24          | 2.00          | 22          | 1.00          | 20          |
| $5 \times 10^{-4}$ | 2.00         | 24          | 1.50          | 22          | 1.00          | 20          | 0.50          | 18          |
| 1              | 2.00          | 24          | 1.50          | 22          | 1.00          | 20          | 0.50          | 18          |
The stress mutation coefficient is defined as the ratio of the advanced abutment pressure in scheme $a$ and $b$ to that with the same thickness. The abutment pressure at 10, 20, 30, 40, and 50 m of the advanced influenced longwall was selected for comparative analysis (Figure 11).

When the longwall mining from thin roof zone to thick roof zone (Figure 11(a)), the stress mutation coefficient peaks in the thick roof zone. At the thinnest RTVZ, the minimum abutment pressure mutation coefficient is about 0.85, while at the thickest RTVZ, the maximum abutment pressure mutation coefficient is about 1.08.

When the longwall mining from thick roof zone to thin roof zone, the stress mutation coefficient increases first, decreases and finally increases. At the thickest RTVZ, the maximum abutment pressure mutation coefficient is about 1.15, while at the thinnest RTVZ, the minimum abutment pressure mutation coefficient is about 0.85 (Figure 11(b)).

The mining of longwall causes the increase of mining-induced stress coefficient in the TAFC, the reason of which is the local stress concentration caused by the thickness/property change of roof or coal seam in the TAFC. Therefore, this paper compares the results of mining stress changes caused by the VCST and the VRT (shown in Table 5). It can be seen that compared with the VCST, the change of mining stress concentration coefficient caused by the simulation result is relatively small. The size of the TAFC may incur difference: the smaller the VCST range, the larger the stress concentration coefficient caused by longwall mining. In general, the variation range of roof thickness is wide, and the stress concentration coefficient is small, which is difficult to attract the attention of mining staff. However, the analysis shows that the stress mutation coefficient increases to a certain extent in the thickest roof zone. When the longwall mining to this zone, the advanced abutment pressure and the mutation tectonic stress are superimposed, increasing the possibility of rock bursts. Therefore, when the longwall mining pushes from thin roof zone to thick roof zone or vice versa, the stress anomaly should be closely monitored where the roof is the thickest.

4.3. Energy distribution in RTVZ

Elastic energy density $W_E$ of coal/rock mass under triaxial stress can be expressed as (Xie et al. 2005; Jiang et al. 2010):
WE = \frac{\sigma_1^2 + \sigma_2^2 + \sigma_3^2 - 2\mu \cdot \sigma_1 \cdot \sigma_2 - 2\mu \cdot \sigma_2 \cdot \sigma_3 - 2\mu \cdot \sigma_1 \cdot \sigma_3}{2E} \tag{9}

Where \( \sigma_1, \sigma_2, \text{ and } \sigma_3 \) are the maximum, intermediate and minimum principal stresses, respectively; \( E \) is elastic modulus; \( \mu \) is Poisson’s ratio.
To study the influence of VRT on the elastic energy density accumulated in front of the longwall, the elastic energy density in the mining process was obtained from Equation (9) after it is sectioned ($z = 37$ m). Then the energy density accumulation cloud map of each section is combined to directly reflect the energy accumulation (Figure 12 (a, b)). Figure 13 shows the increased elastic energy density under different schemes (in relation to VRT). The increased elastic energy density is calculated by deducting the initial elastic energy density from the elastic energy density under different RTV conditions. In addition, the initial elastic energy density ($W_E = 5.11E + 04$ J/m$^3$) was obtained by simulation under the condition that the thickness of the roof remains unchanged.

When the longwall mining pushes from thin roof zone to thick roof zone for 20 m, two elastic energy density increase zones appear 50 m in front of the longwall.

**Figure 12.** (a) Section cloud map of elastic energy density with the longwall mining from thin roof zone to thick roof zone. (b) Section cloud map of elastic energy density with the longwall mining from thick roof zone to thin roof zone.
One maximum elastic energy density increase is $1.64 \times 10^4 \text{J/m}^3$, and the other is $1.8 \times 10^3 \text{J/m}^3$. But when the longwall mining pushes from thick roof zone to thin roof zone, only one elastic energy density increase zone (120 m ahead) appears, and the maximum elastic energy density increase is $1.39 \times 10^4 \text{J/m}^3$.

When the longwall mining pushes from thin roof zone to thick roof zone or the vice versa for 100 m, only one elastic energy density increase zone appears. But when the advance influenced range is 170 and 100 m, respectively, the maximum elastic energy density increases are $8.56 \times 10^4 \text{J/m}^3$ and $8.41 \times 10^4 \text{J/m}^3$. When the longwall mining pushes from thin roof zone to thick roof zone or the vice versa for 200 m, still one elastic energy density increase zone appears, and the maximum elastic energy density increases are $1.45 \times 10^5$ and $1.38 \times 10^5 \text{J/m}^3$, respectively.

### 4.4. Plastic zone distribution in RTVZ

The plastic zone distribution can inform us of fracture behavior and roof caving possibilities in coal or strata (Mu et al. 2021). The fracture behavior of coal/rock mass is tensile fracture and shear fracture (Zhou et al. 2020; Fu et al. 2021). Based on the minimum potential energy theory, Rezaei (Rezaei et al. 2015b, 2017, 2018) studied the height of the destressed zone above the mined panel in longwall coal mining, and obtained that the height of the roof destressed zone was $2.02 - 57.8$ times that of the extracted coal seam, and the larger the overburden, the thicker the roof destressed zone. Therefore, after the longwall mining, the basic roof above the coal seam has been destroyed, forming a plastic zone. The plastic zone distribution in coal seam and basic roof (Figure 14) is selected of the influence of VRT on rock mass failure.

Figure 14 (a, b) show the plastic zone distribution in coal seam ($z = 37 \text{ m}$) and roof ($z = 60 \text{ m}$) in the longwall mining pushes from thin roof zone to thick roof zone. During this process, shear fracture mainly exists in the coal seam, but in the area where the roof has collapsed, tensile fractures appears. At the same time, affected by the advanced abutment pressure, the first plastic zone is formed in the front of
the longwall. In the RTVZ, the superimposed influence of tectonic stress change and advanced abutment pressure, coal/rock may exceed its bearing limit and form the second plastic zone. In addition, when the longwall mining pushes from thin roof zone to thick roof zone, the first pressure strength of the roof is low, but the subsequent periodic pressure can be obviously observed, and the roof is more likely to break, which is easy to induce large dynamic load.

Figure 14. (a) Distribution of plastic zone when pushed from thin roof zone to thick roof zone ($z = 37m$). (b) Distribution of roof plastic zone when pushed from thin roof zone to thick roof zone ($Z = 60m$). (c) Distribution of plastic zone when pushed from thin roof zone to thick roof zone ($z = 37m$). (d) Distribution of roof plastic zone when pushed from thick roof zone to thin roof zone ($Z = 60m$).
Figure 14 (c, d) show the plastic zone distribution in coal seam ($z = 37$ m) and roof ($z = 60$ m) in the longwall mining pushes from thick roof zone to thin roof zone. During this process, the first plastic zone is formed in the front of the longwall due to the superposition influence of tectonic stress change and advanced abutment pressure. Because the roof is thicker at the initial stage of mining, the first roof fracture is more intense. However, as the roof caving afterwards is incomplete, the periodic fracture of the longwall is not obvious; only when the longwall mining pushes to the roof thinning zone, the periodic roof fracture appears again.

5. Mechanism of rock bursts induced by coal mining

When the longwall mining pushes from thin roof zone to thick roof zone, the static load stress follows a decrease–increase–decrease pattern (Figure 11(a)). The second peak stress zone is formed in thick roof zone when the advanced abutment pressure is transferred from the thinning zone to the thickening zone. Under the influence of mining, there may exist two potential rock burst areas in front of the longwall: the

![Figure 15. (a) Schematic of the rock burst mechanisms induced by RTVZ with the longwall mining from thin roof zone to thick roof zone. (b) Schematic of the rock burst mechanisms induced by RTVZ with the longwall mining from thick roof zone to thin roof zone.](image)
advanced abutment pressure peak value area and the area with second peak stress plus mining stress. The second peak stress zone is located further ahead of the longwall, and the impact energy generated will mainly be released to the two roadways, thus increasing the possibilities of rock bursts (Figure 15(a)).

When the longwall mining pushes from thick roof zone to thin roof zone, the static load stress follows an increase–decrease–increase pattern (Figure 11(b)). Only one peak stress is formed in thick roof zone when the advanced abutment pressure is transferred from the thickening zone to the thinning zone. When superimposed with mining stress, only one potential rock burst zone is formed in front of the longwall, but the impact range is wider, and the rock burst energy is higher than that of stable roof thickness (Figure 15b).

Therefore, when longwall mining happens in the RTVZ, the elastic energy accumulated in front of the longwall can easily trigger rock bursts due to the superposition of the advanced abutment pressure and the tectonic stress. Current rock bursts control techniques can be classified into two types: preventative controls and mitigating controls. Mitigating technique can prevent and control rock bursts induced by the RTVZ, including hydraulic fracturing, water infusion, stress relief drilling, bump cutter and explosive charge (Wei et al. 2018). When the longwall mining pushes from thin roof zone to thick roof zone, the main task is to decrease the second peak stress in the thick roof zone, and therefore avoid the formation of the second rock burst zone. When the longwall mining pushes from thick roof zone to thin roof zone, the potential rock bursts zone is located near the coal seam, so prevention methods are mainly aiming at transferring the stress to the deeper coal/rock mass (Konicek et al. 2011). Concurrently, in order to minimize the impact of rock bursts, roadway support should be strengthened to reduce the impact of dynamic load on the roadway.

6. Conclusions

Due to the special sedimentation of coal-bearing strata, the roofs with a large variation in thickness may account for potential rock bursts. Theoretical analysis and numerical modeling are applied to the two cases, LW103 in Yitai Coal Mine and LW3102 in Menkeqing Coal Mine, to investigate the stress anomaly of the mining coal seam and the rock burst mechanisms in the RTVZ. The main conclusions are as follows:

1. The two cases demonstrate that there exists obvious stress anomaly in the RTVZ. Rock bursts are more likely to happen in the thick roof zone, where the stress and energy are significantly concentrated. The stress monitoring value in thick roof zone is 1.8–2.6 times that in thin roof zone.

2. The coal seam with a thicker hard roof can have high initial stress, and the range of the stress can vary significantly with the increasing variation in the roof thickness or the roof properties. When the elastic modulus ratio of the two roofs $E_{Rs}/E_{Rh}$ is constant, the vertical stresses ratio of the coal seam $\sigma_d/\sigma_c$ decreases linearly with the increase of the hard roof thickness ratio $H_{hc}/H_{ha}$. When $H_{hc}/H_{ha}$ constant, $\sigma_d/\sigma_c$ is inversely proportional to $E_{Rs}/E_{Rh}$. 

1826 X. BAI ET AL.
3. When the longwall mining pushes from thin roof zone to thick roof zone, the static load stress in the coal seam follows a decrease–increase–decrease pattern; when the longwall mining pushes from thick roof zone to thin roof zone, the static stress in the coal seam followed an increase–decrease–increase pattern. In the thick roof zone, the superposition of the advanced abutment pressure and the increased initial stress will result in high-stress concentration, where the stress mutation coefficient value can reach 1.08–1.15.

4. During mining, there exist higher rock burst risks in the roadway near thick roof zone, where more intensive elastic energy is released in the coal/rock mass. Also, it is more likely to have a significant dynamic load in the thin roof zone due to easier roof breakage.

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No potential conflict of interest was reported by the authors.

**Availability of data and material**
Not applicable.

**Code availability**
Not applicable.

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