The Mechanical Analysis of Dynamic Disturbance and Static Stress under Different Mining Methods

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Research Article

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The Mechanical Analysis of Dynamic Disturbance and Static Stress under Different Mining Methods

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Abstract: In order to study the occurrence mechanism of rock-burst accidents under different mining methods, the overburden structural characteristics during long-wall face mining period were studied in detail, and the Elastic Foundation Beam theory was used to analyze the dynamic disturbance and static stress under different mining methods. The results show that, the deflection of the main roof and the composite beam can be calculated and then the energy of them contained; due to the difficult for gangues to support the fractured main roof, the scope of caved overburden is largest and the coal seam share the largest volume of the hanging overburden; the large cutting height mining have the max the concentration coefficient and the thin seam or the top slice mining have the min the concentration coefficient; the structural characteristics of near field key strata largely depend on caving height of the gob, and the deflection and the weighting interval of the main roof changes with variation of mining methods, and then their energy released. Above all, it can be conclude that mining method has large impact on dynamic disturbance induced by the main roof, and further analysis indicate that the structural characteristics of both far field and near field key strata under different mining methods lead to this difference; the mining depth, the proportion coefficient, the tensile strength of the main roof, the main roof’s thickness have large impact on the deflection of the beam and energy released by the main roof and the composite beam, and the elasticity modulus of the main roof, the blank space height in a voussoir beam structure have little impact on the deflection and energy released.

Key words: rock-burst accidents; dynamic disturbance; static stress; different mining methods; Elastic Foundation Beam theory; structural characteristics

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1 Introduction

Rock-burst accidents are currently considered to be one of the most severe threats to underground safety. Its occurrence is largely related to the mechanical property of coal seam and surrounding rock mass, and the dynamic disturbance and static stress distribution conditions, as well. Thus, a series of studies on dynamic disturbance which induced the rock burst were conducted (Zubelewicz and Mróz 1983); many scholars all pointed out that the mechanical mechanism of rock burst induced by static stress distribution and dynamic distribution (Li et al. 2008; Li et al. 2008; Liu et al. 2014; Zuo et al. 2008; Pan et al. 2012; He et al. 2014; Dou et al. 2015). However, these studies were under specific mining layouts or mining methods, and the influence of mining methods on rock burst had rarely been contrasted and studied specifically. Accidents statistics show that in thick seams mining period, 91% of the accidents took place in roadways, the failure length of the roadways ranged from 90~150 m and strong mine earthquake took place almost every time. However, in thin seam mining, 86% of the accidents took place 0~15m from the face-end in mining face or 0~20m from face-end in gob-side tailgates, and most of the accidents were slightly. Therefore, it is can be seen that rock-burst accidents show different characteristics when mining methods changed.

In order to solve these issues, strata behavior under different mining methods should be paid more attention, firstly. It was found that long-wall face overburden have different structural characteristics and different strata behavior regularities when mining layout or mining methods changes (Liu et al. 2017). It was also found that the main roof can form a cantilever beam when the large cutting height mining method was applied to a long-wall face or the overburden was made up of hard rocks (Liu et al. 2015). It was found that the main roof usually form a voussoir beam when a medium-thickness coal seam or a top slice of thick seam was extracted or top-coal caving mining method was used to extracted thick seam (Qian et al. 2010). It was found that the main roof can form a long bent beam when a thin seam was extracted (Jia 2010). As can be seen, mining method lead to different force condition on main roof which in turn affect the dynamic disturbance energy released. Based on this, it was comparatively studied the dynamic disturbance characteristic of fully-mechanized long-wall faces and fully-mechanized top-coal caving faces (Li et al. 2018). As rock-burst accidents have been recorded in various mining methods, the dynamic disturbance characteristic of more mining methods should be studied to find the key factor and put forward target preventions.

When it comes to the dynamic disturbance, the fracture position of main roof is of great importance. It is because the bending energy stored in roof was released when roof breaking and the fracture position is usually ahead of the mining face. It was pointed out that the advanced fracture of main roof could induce a rebound at its clamped part which is the main pattern for energy released (Qian et al. 2010). Due to the clamped effect above rib, the fracture position can largely determine the max hanging length of the main roof and then the amount of the energy released. Thus, the accurate fracture position is of great importance. According to the Elastic Foundation Beam theory (Yang et al. 2018), surrounding rock mechanical quality and stress condition of the clamped end of main roof above rib can largely affect the position. Beside, the force exerted on the hanging end of can largely affect the position, too.

Above all, the accurate mechanical model which can take mechanical quality and force condition into account is needed to be developed to describe the dynamic disturbance under different mining methods. Considering the energy released by the loading strata above main roof, the energy released by composite beam effect should be taken into account, too.

When it comes to the static stress distribution, the structural characteristics evolution of far field overburden under mining methods cannot be omitted. It was qualitatively described the evolution of the static stress distribution with long-wall face advancing according to field measurement (Gao 2016). It was summarized the static stress distribution of three typical mining layouts from field measurement and gave suggested peak values of abutment pressure (Xie et al. 2016). However, few quantitative studies can be found
about the evolution of the static stress distribution with the mining methods changing. In fact, its evolution is a
result of loads transferring of far field overburden hanging in-air as pressure arch hypothesis stated. When the
mining methods change, the loads near field surrounding rock also change, too. Base on this, mechanical
model can be established to quantitatively describe the evolution of the static stress distribution in rib.

This research establishes theoretical models that can consider the effect of mining methods. The
arrangement is listed as follows. In Section 2, the theoretical model for dynamic disturbance calculation was
established according to the structural characteristics of overburden and the composite beam theory. The
calculation principle for energy release of overburden was given according to the Elastic Foundation Beam
theory. In Section 3, the structural characteristics of far field overburden under different mining methods was
studied and the simplified theoretical models were establishes according to the structural characteristics. Based
on the models, the evolution law for static stress under different mining methods was revealed by Elastic
Foundation Beam theory and the suggested static stress distributions under different mining methods were
given. In Section 4, structural characteristics of near field overburden under different mining methods were
given and corresponding forces exerted on the hanging end were calculated. The results were embedded in
calculation method proposed in Section 2. According the calculations the deflection and the bending moment
distribution of the beam were got, the energy released by the overburden were listed and discussed. The results
can reveal the influence of different mining methods on the dynamic disturbance and static stress distribution.
To this end, mechanical models are established to resume the force conditions induced by the overburden
structure corresponding to different mining layouts. The Elastic Foundation Beam model was used to explain
static stress distribution as well as the dynamic disturbance energy under different mining methods.

2 Calculation Principles for Dynamic Disturbance Released by Overburden

2.1 Characteristics of Overburden Structure in Long-wall Face

It is well known that coal mining always accompany with rock strata fracture. Literatures (Qian et al.
2010; Jia 2010) pointed out that the near field key strata (zone II in Fig.1(b)) could form a cantilever beam or a
voussior beam structure when the longitudinal section was taken from the middle of mining face after it was
fractured, as show in Fig.1(b). Meanwhile, the key strata fractured in the form of “O-X” when horizontal
section was taken from the middle of main roof or inferior key strata after they was fractured, as show in
Fig.1(a). The structures undertook the above loading and protected the workface from the loading above. With
the breakage of overburden and the caving of the fractured overburden, the dynamic disturbance formed and
the energy was released. As can be seen in Fig.1(b), Block B and C were supported by supports in the
workface and the gangue in the gob. They could hardly disturb the coal seam. Thus, if we want to search the
dynamic disturbance which give rise to rock burst, we should pay more attention to block A. What more, the
literatures (Qian et al. 2010; Jia 2010) also pointed out that the far field key strata (zone III in Fig.1(b))
undertook the overlying load and transfer these loading to coal seam forward and gangue behind as a
framework. As a result, static stress concentration formed before the mining face.
2.2 Mechanism of the Composite Beam and the Loading on the Beam

As indicated in above section, dynamic disturbance shows up when the cantilever fractures. Thus, the energy contains before and after it fractures should be studied. Firstly, the loading on the beam which induce the energy should be calculated. Usually, the overburden is divided into groups according to the composite beam theory:

\[ Q = Q_1 + Q_2 + \ldots + Q_n \]  
\[ M = M_1 + M_2 + \ldots + M_n \]

According to the theory, the shear force and the bending moment of the composite beam are composed of that of each rock stratum and each rock stratum of the composite beam shear a common curvature.

\[ k_i = \frac{1}{\rho_i} = \frac{(M_i)}{E_i J_i} \]

According to this theory, the key stratum above the composite beam could be found and the composite beam is separated from its overlying key stratum by their different strength and gravity. Thus, the cantilever part of the main roof needs not to bear the pressure from the key stratum. In consideration of the self-supporting ability of the composite beam, the loading on main roof should be converted to the Eq. (4).

\[ (q_n)_1 = \frac{E_i h_i^1 (\gamma h_i + \gamma_2 h_2 + \ldots + \gamma_n h_n)}{E_i h_i^1 + E_2 h_2^1 + \ldots + E_n h_n^1} \quad (+\infty < x < b) \]

Where \((q_n)_1\) is the loading exerted on the cantilever of the main roof.

When it comes to the clamped part of main roof above coal seam, the loading will change. It is obvious that the loading on the main roof at infinity is \(\gamma H\), \(H\) is the depth of panel below, \(\gamma\) is unit weight of overlying strata.

\[ q(x) = \gamma H \quad (+\infty < x < a) \]

As can be seen in Fig.2, due to the stress transfer of rock strata above the inferior key strata as well as the loading transfer of the cantilever part, the loading exerted on the clamped part of the cantilever beam seem a wave. Thus, a linear wave is used to describe the real wave, and the formula can be expressed as Eq. (6).
Fig. 2 Stress state of the composite beam before and after being fractured. a before the fracture of main roof, b after the fracture of main roof, c mechanical model

\[ q(x) = \gamma H + \frac{d-x}{a} (K-1)\gamma H \quad (0 < x < a) \]  

(6)

In consideration of the unseparated part of the cantilever beam from the inferior key strata, the stress between 0 and b can be calculated as follows:

\[ q(x) = (q_a)_1 + \frac{b-x}{b} K\gamma H - (q_a)_1 \quad (b < x < 0) \]  

(7)
Above all, the deflection of the main roof and the composite beam can be calculate and then the energy of them contained.

2.3 Deflection of the Composite Beam Before and After it Fracture

2.3.1 Deflection of the composite beam before it fracture

Before the calculation, the coal seam and the rock strata below the clamped part should be seen as an elastic foundations and then the Elastic Foundation Beam theory (Guo et al. 2018; Liu et al. 2018) is used.

\[ p = -ky \]  (8)

Where \( p \) is vertical force, \( y \) is vertical displacement of the foundation, \( k \) is the proportion coefficient of \( p \) and \( y \).

Zone I in Fig. 2(c) shows the stress conditions and boundary conditions of main roof. In the model, the main roof is seen as a voussoir beam structure which makes up of a cantilever beam and two forces (Q and \( N' \)). The differential equation of bending deformation can be got according to Timoshenko:

\[ EI \frac{d^4 y}{dx^4} + N \frac{d^2 y}{dx^2} = q(x) - ky \quad (0 \leq x < \infty) \]  (9)

According to the literature (Qian et al. 2010), the solution to Eq. (9) is made as follows:

\[ y(x) = \frac{1}{2} e^{-ax} \left[ (A + C) \cos \beta x + (B + D) \sin \beta x \right] + \frac{1}{2} e^{ax} \left[ (A - C) \cos \beta x + (B - D) \sin \beta x \right] + \frac{q(x)}{k} \]  (10)

Where \( a = \sqrt{\frac{k}{4EI}} \left( \frac{T}{4EI} \right)^2 \), \( \beta = \sqrt{\frac{k}{4EI}} \left( \frac{T}{4EI} \right)^2 \), \( EI \) is the stiffness of the beam, \( T \) is the horizontal force exert on the beam.

Because of \( x \to \infty, \ y \to \text{constant} \), coefficient of \( e^{-ax} \) in Eq. (10) should be equal to 0, thus:

\[ A + C = 0 \]  (11)
\[ B + D = 0 \]  (12)
\[ y = \frac{\gamma H}{k} \]  (13)

Above all, the simplified form for Eq. (9) is:

\[ y(x) = e^{-ax} [A \cos \beta x + B \sin \beta x] + \frac{q(x)}{k} \quad (a \leq x < \infty) \]  (14)

Where \( A = \frac{M_o}{EI} \left( \frac{k}{EI} \right) + \frac{2aQ_o}{k} \), \( B = \frac{2aM_o}{2EI} \left( \frac{k}{EI} \right) + \frac{T}{2IE} \), \( M_o \) is the bending moment.

\( M_o \) and \( T \) is shearing force at \( x_o = 0 \), which can be got by the simple mechanical calculation on the cantilever beam.

2.3.2 Deflection of the composite beam after it fracturing and influential parameters

According to the conditions in zone II in Fig. 2(c) and method above, the deflection and bending moment after the main roof fracture can be calculated. It can be seen in Eq. (14) that the deflection of the main roof depends on many factors. These factors can be concluded as follow:

1) The value of \( M_o, q_o \) and \( T_o \) at the end of the cantilever depend on the force condition of the cantilever part of the main roof and the abutment pressure, therefore, the force condition and the abutment pressure should be discussed.

2) The value of \( k \) and \( EI \) are depended on the mechanical property the main roof and the coal seam. Thus, the mechanical property should be discussed.
3) The value of loading $q(x)$ exerted on the main roof are depended on depth of the main roof, the thickness of the loading layer and the abutment pressure distributed on the main roof. These parameters also should be discussed.

2.4 Mechanism of Energy Release of Overburden

Generally, when it comes to the dynamic disturbance caused by energy release of overburden, literatures pay attention to the main roof. However, as can be seen in Fig.2, when the cantilever fracture, the rock strata above it fracture and release energy as well. Although we regard these rock strata as burden exerted on the main roof when calculating the maximal bending moment and limit length of the main roof, the energy they released can be omitted when it comes to the dynamic disturbance caused by energy release of overburden. Thus, the composite beam is put forward and serve as a revised model to calculate the energy release of overburden.

Use the model above, the deflection before and after the composite beam fracture was got. Then, the energy contained in the composite beam due to its bend before and after the composite beam fracture can be calculated. Thus, we got the energy the composite beam released. The energy contained in the composite beam before it fracturing is:

$$U_1 = \int y(x)q(x)dx$$

The energy contained in the composite beam after it fracturing is:

$$U_2 = \int y(x)q(x)dx$$

Therefore, the released energy of the composite beam is:

$$U = U_1 - U_2$$

3 Structural Characteristics of Far Field Overburden under Different Mining Methods and Its Influence on Static Stress

3.1 Characteristics of Far Field Overburden Structure under Different Mining Methods

Fig.3 shows far field overburden structures of four typical mining methods, including fully mechanized mining top slice (Fig.3(a)), fully mechanized mining bottom slice (Fig.3(b)) (its overburden structure also can used to express that of fully mechanized mining close-seam or fully mechanized depressurized one), top-coal caving mining the whole coal seam (Fig.3(c)) and fully mechanized large cutting height mining whole coal seam (Fig.3(d)).
It is well known that hydraulic supports in the workface need not to bear all of the overburden hanging in the midair above it. It is because the key strata serve as the framework which bear the overburden and transfer its loading to the coal seam forward and the gangue behind as an arch or a each ends clamped beam. Obviously, the clamped ends share the loading of the rock strata hanging in midair above the workface. Thus, the abutment pressure formed. Meanwhile, the abutment pressure distribute on the coal seam can on behalf of the volume of the hanging overburden.

As can be seen in Fig. 3(a), when the fully mechanized mining method is applied to mining a thin seam or a top slice of thick seam which mining height is relative low, caved gangues are usually high enough to backfill the gob well. In this situation, if there is small amount deformation of main roof or small rotation of the fractured main roof, the main roof could touch the gangues and be supported by the gangues soon after the coal being excavated. As a result, the length of the hanging overburden is relative small. In Fig. 3(b), when the fully mechanized mining bottom slice method is applied to the panel, the gob was backfilled worst. The overall excavated height is largest and caved gangues are lowest of all mining method. Thus, the rotation of the fractured main roof was required to be big enough. The structure of main roof under this situation is a voussior beam or a semiaich or a clamped beam at one end. Despite of the difficulty to backfill the gob, fortunately, the fractured overburden does not have the ability to hang a certain length as an integrated overburden. The overburden will backfill the gob immediately like stones drop. Thus, the overburden would touch the gangues
and be supported by the gangues soon after the coal being excavated. As a result, the length of the arch is relative small. In Fig.3(c), the top-coal caving mining the whole coal seam method is applied. As can be seen, the caving height of the gob is higher than mining the top slice and lower than mining the bottom slice because of insufficient of caved top-coal. Thus, the required rotation to be supported by the gangues is smaller than mining the bottom slice and bigger than mining the top slice. Meanwhile, in this situation, the overburden still have the ability to hang a certain length. As a result, the length of the hanging overburden is relative bigger and the coal seam need to share more loading. Thus, the abutment pressure distribute on the coal seam is larger than that of mining bottom slice or mining the top slice. In Fig.3(d), fully mechanized large cutting height mining method is applied. As can be seen, the caving height of the gob is highest of all the mining method. The required rotation for block B is biggest of all the mining method and then is easy to lose it stability as a voussior beam or a semiaich for the main roof. It is common to see the main roof forming a cantilever beam clamped at one end as shown in Fig.3(d). Due to the difficult for gangues to support the fractured main roof, the scope of caved overburden is largest and the coal seam share the largest volume of the hanging overburden. Therefore, the abutment pressure distribute on the coal seam and the main roof is the largest of all the mining method.

Besides, Fig.4 show the function of the gob-side coal pillar to share loading and compare the abutment pressure in a longwall mining remaining coal pillar to a non pillar one's. As can be seen, the coal pillar can share the loading of overburden and reduce the abutment pressure distribute on the coal seam and the main roof. In all, the non-pillar mining face have the bigger abutment pressure than the remaining coal pillar face.

![Fig.4 Overburden Structure of different mining layouts.](image)

(a) retain the coal pillar; (b) un-retained the coal pillar;

**3.2 Laws for static stress evolution under different structural characteristics**

The simplified models to calculate the abutment pressure is shown in Fig.5, among this the key strata belongs to mining-induced fracture zone and the rock strata below belongs to mining-induced caving zone.
The simplified calculation method for the abutment pressure can be got according to Eq. (8) and Eq. (14):
\[
p = -ke^{-ax}[A\cos \beta x + B\sin \beta x] - q(x) \quad (0 \leq x < \infty)
\]  
(18)

When \( x \to \infty \), \( p = -q(x) = -\gamma H_d \).

Where the main roof is seen as a doubly-clamped beam and meets the follows: \( L = 2L_0 \), \( M_0 = \frac{1}{2}qL_0^2 \).

\( Q_0 = qL_0 \). Supposing that \( y_{2\theta} \big/ H \), and then:
\[
\Delta = H - \sum h(K_p - 1) - y_{2\theta} \approx H - \sum h(K_p - 1) = 0
\]  
(19)

Where \( \sum h = \frac{H}{K_p - 1}, \sum \frac{h}{L} = \tan \theta \), and \( L = 2L_0 = \frac{H \cot \theta}{K_p - 1} \).

Above all, the relationship between the mining height and the static stress (or called abutment pressure) distributes on coal seam or the main roof is obtained.

In Fig.6, the concentration coefficient of static stress also represent the peak of abutment pressure. The angle \( \theta \) represent the hanging length of the key strata and then reflect its self-supporting capacity when the caving height is a certain. The bulking coefficient of the rock blocks (\( K_p \)) represent caving height of the gob when the mining height is a certain.
Fig. 6 Factor analysis for concentration coefficient of static stress. a \( K_p = 1.05 \); b \( K_p = 1.1 \); c \( K_p = 1.15 \); d \( K_p = 1.2 \)

It can be seen that with the increase of the mining height, the concentration coefficient of static stress increase. Thus, the mining method can largely effect the concentration coefficient of static stress. The large cutting height mining have the max the concentration coefficient and the thin seam or the top slice mining have the min the concentration coefficient. Beside, with the increase of angle \( \theta \), the concentration coefficient decrease. It is easy to know that the larger angle \( \theta \) is, the weaker its self–supporting capacity is when the caving height is a certain. Thus, the fully mechanized mining bottom slice (Fig.3(b)) have a smaller concentration coefficient than the large cutting height mining one’s.

Furthermore, with the increase of the bulking coefficient of the rock blocks, the concentration coefficient decreases. Therefore, the top-coal caving mining (Fig.3(c)) has a smaller concentration coefficient than the fully mechanized large cutting height mining. These conclusions were confirmed by field measurement and literatures as shown in Fig.7.

Fig. 7 Distribution of abutment pressure under various mining layouts. a coal caving mining; b non-pillar mining; c protective seam mining

In consideration of the tiny differences between the static stress exert on the coal seam and the clamped end of the composite, the static stress exert on the clamped end of the composite can be represented by that on the coal seam. Thus, stress condition of the clamped end of the composite which can largely effect the deflection of the composite beam is got and the dynamic disturbance of the composite beam can be calculated in a more realistic way.

4 Structural Characteristics of Near Field Key Strata under Different Mining Methods and Its Influence on Dynamic Disturbance

There are many parameters will influence the deflection of the composite beam and then the energy released. These parameters have closely link with the near field key strata structure of different mining methods. Thus, mining method can largely effect the energy released.

4.1 Structural Characteristics and Force Condition of Near Field Key Strata under Different Mining Methods

As can be seen in Fig.3 and Fig.5, mining methods have large impact on caving height of the gob as well as the static stress distribute on the main roof. Researches show that the structural characteristics of near field key strata largely depend on caving height of the gob. Thus, the deflection and the weighting interval of the main roof changes with variation of mining methods, and then their energy released.

4.1.1 Mechanical calculation on the bending moment and shearing force when a top slice of thick coal seam or a thin seam mining
Fig. 8 Overburden structure under a top slice of thick coal seam or a thin seam mining conditions. a structure I; b structure II; c structure III; d structure IV

In Fig. 8(a), when a top slice of thick coal seam or a thin seam is extracted, the gob can be backfilled well by the caved gangues. A critical state in this model is that once the main roof bent and touch the gangues the main roof fracture immediately. In this situation, the main roof own the shortest weighting interval and smallest energy. The main roof form a voussoir beam and the rotation of rock blocks approaches zero. According to the equilibrium conditions and a voussoir beam theory, $M_0$, $Q_0$ and $T$ are given as follows:
\[
\begin{align*}
M_0 &= EIy_0'' = \frac{1}{2} qL^2 + RL + T \frac{H}{2} \\
Q_0 &= EIy_0'' + NY_0 = qL + R_l
\end{align*}
\] (20)

To simplify the calculations, the length of the block B can be calculated as follow:

\[
\begin{align*}
T &= \frac{2qL^2}{2H - L \sin \theta_1} \\
R_l &= \frac{4H - 3 \sin \theta_1 L}{2[H - \sin \theta_1 L]} qL
\end{align*}
\] (21)

Where \( \theta_1 \) approaches to 0, \( \Delta \approx \frac{5}{4} \sin \theta_1 L + \omega = \omega' \), \( T = \frac{qL^2}{H} \), \( R_l = qL \), \( M_i = 2qL^2 \), \( Q_0 = 2qL \), and

\[
L = \sqrt{\frac{R_l H^2 - (K - 1)\gamma H b^2}{12q}}.
\]

According to the above calculations, the deflection and the bending moment of the beam before and after it is fractured can get. Thus, the energy released can get.
Fig. 9 Chart of energy released about structure I. a condition I; b condition II; c condition III

Fig. 9(a) show the deflection and the bending moment of the beam, the energy released both of the main roof and the composite beam, as well. It can be seen that the proportion coefficient $k$ which reflect the stiffness can largely effect the deflection of the beam and then energy released. However, the influence of mining depth on the deflection of the beam and energy released is relatively small. Besides, the comparison of the energy released of the main roof and the composite beam show clear difference. Thus, the energy released by the loading layer should not be omitted.

Fig. 9(b) show the influence of mining depth and the ultimate tensile strength on the deflection of the beam and energy released of the main roof and the composite beam. It can be seen clearly that with the increase of the mining depth, the deflection of the beam increases and the energy released increases, too. Besides, the increase of main roof’s ultimate tensile strength also lead to a increase of deflection, weighting interval and then energy release of both the main roof and the composite beam.

Fig. 9(c) show the influence of main roof’s Elastic Modulus and $k$ on the deflection of the beam and energy released of the main roof and the composite beam. It also can be seen that the Elastic Modulus has little impact on the deflection and energy release and the proportion coefficient $k$ has largely impact.

4.1.2 Mechanical calculation on the bending moment and shearing force when a medium-thickness coal seam mining

In Fig. 8(b), the gob is backfilled worse than that in Fig. 8(a). The main roof form a voussoir beam structure. With coal mining, the hanging length of the cantilever part of the main roof increase. Then, the cantilever part bent and fracture.

$$
\begin{align*}
M_0 &= EI_y_0 = \frac{1}{2} qL^2 + R_i L + \frac{H}{2} \\
Q_0 &= EI_y_0 \theta + N_{y_0} = qL + R_i 
\end{align*}
$$

(22)

To simplify the calculations, the length of the block B can be calculated as follow:

$$
\begin{align*}
T &= \frac{2qL}{2H - L \sin \theta_i} \\
R_i &= \frac{4H - 3\sin \theta_i L}{2(2H - \sin \theta_i L)} qL 
\end{align*}
$$

(23)

In consideration of the deflection $\omega$ is relatively small when compare it to $\Delta$, and the $\Delta$ can be calculated as follows:

$$
\begin{align*}
M_0 &= \frac{qL^2}{2} + \frac{5H - 3\Delta}{5H - 2\Delta} qL^2 + \frac{(K-1)yH \times b \times b}{6} + \frac{5qL^2}{5H - 2\Delta} \frac{H}{2} = 2qL^2 + \frac{(K-1)yH \times b \times b}{6}
\end{align*}
$$

(24)
Where \[ \Delta = \frac{5}{4} \sin \theta_1 L + \omega = \frac{5}{4} \sin \theta_1 L , \quad \sin \theta_1 L < H , \quad \Delta < \frac{5}{4} H , \quad T = \frac{5qL^2}{5H-2\Delta} , \quad R_i = \frac{5H-3\Delta}{5H-2\Delta} qL . \]
\[ L = \sqrt{\frac{R_i H^2 - (K-1)\gamma H b^2}{12q}} . \]

In this situation, \( \Delta \) should be discussed, the results is shown in Fig.10. Fig.10 shows the influence of blank space height \( \Delta \) and the concentration coefficient of static stress \( K \). As can be seen, the blank space height has little impact on the deflection and energy released. However, the concentration coefficient can clearly impact the deflection and energy released. The bigger concentration coefficient is, the larger deflection and the more energy released.

![Fig.10 Chart of energy released under the influence of blank space height](image)

### 4.1.3 Mechanical calculation on the bending moment and shearing force when a thick coal seam mining with top coal caving method

In Fig.8(c) the gob is backfilled worse than that in Fig.8(b) The main roof form a semiaich structure. With coal mining, the hanging length of the cantilever part of the main roof increase. Then, the cantilever part bent and fracture.

\[
\begin{align*}
M_o &= EI\gamma_0 = \frac{1}{2} qL^2 + R_i L + T \frac{H}{2} - T\Delta s - F_z = \frac{1}{2} qL^2 + R_i L + \frac{H(qL^2 - 2R_i L)}{4(\Delta - H)} \\
Q_o &= EI\gamma_0 + N\gamma_0 = qL + R_i
\end{align*}
\]

Where \( T(\Delta - H) = (R_i - R) L , \quad 0 \leq R_i = \frac{qL}{2} - \frac{T(\Delta - H)}{2L} < \frac{qL}{2} , \quad 0 < T \leq \frac{q(x_0 + L)^2}{\Delta - H} . \)

In this situation, \( \Delta \) and \( R_i \) should be discussed, the results is shown in Fig.11. Fig.11 show the influence of blank space height \( \Delta \) and the vertical force \( R_i \) exert the end the main roof. It can be seen that once the blank space height is largely enough for main roof to form a semiarch structure, the blank space height and the vertical force has little impact on the deflection. Because these two factors can influence the force condition of the main roof, the weighting interval will change when factors change and then the energy released changes, too.
4.1.4 Mechanical calculation on the bending moment and shearing force when a thick coal seam mining with large cutting height method

In Fig.8(d) the gob is backfilled worse than that in Fig.8(c), the main roof form a cantilever beam structure. With coal mining, its hanging length increase and rapidly reach the limit. Then, it fracture.

\[
\begin{align*}
M_0 &= EI_0 y' = \frac{1}{2} qL^2 + R_1 L + T \frac{H}{2} + T \Delta s - F_z = \frac{1}{2} qL^2 \\
Q_0 &= E I_0 y'' + N_0 y' = qL
\end{align*}
\]

(26)

Where \( T = 0, \; R_1 = 0, \; L = H \sqrt{\frac{R_1}{3q}}. \)

According to the above calculations, the deflection and the bending moment of the beam before and after it is fractured can get. Thus, the energy released can get.

Fig.12 show the influence of main roof’s thickness \( H \) and the concentration coefficient of static stress. As can be seen, the larger thickness is \( K \), the smaller the deflection is and the longer weighting interval is, the more energy is released, as well. Beside, the larger mining concentration coefficient \( K \) is, the bigger the deflection is and the more energy is released.

Fig.12 Chart of energy released under the influence of main roof’s thickness and the concentration coefficient of static stress

4.2 Comparative Study of the Deflection and Energy Release of Near Field Key Strata under Different Mining Methods

16
Fig. 13 show the influence of mining method on the deflection of the beam and energy released of the main roof and the composite beam. Among this, the deflection and energy released of seven types of typical mining method was introduced.

![Graph showing deflection and energy release](image)

**Fig. 13 Factors discussion of different mining methods**

In situation I and II, a top slice of thick coal seam or a thin seam is extracted. In situation I, the hanging end of the main roof is support by the gangues in gob. In situation II, once the main roof bent and touch the gangues the main roof fracture immediately. As can be seen, the weighting interval and energy released increase obviously in situation I due to the support force.

In situation III, a medium-thickness coal seam is extracted. In situation IV and V, a thick coal seam is extracted with top coal caving method. In situation V and VI, a thick coal seam is extracted with large cutting height method. Among them, the mining method is represented by the concentration coefficient of static stress \( K \) as explained in section 3. As shown, with the increasing of mining height the weighting interval increase, the deflection increase, energy released increase too.

Where \( q \) is the load intensity of main roof; \( H \) is the thickness of the main roof, and \( H = 4 \) m; \( \gamma \) is unit weight of overlying strata, and \( \gamma = 25 \) kN/m\(^3\); \( EI \) is the flexural rigidity of main roof, and \( E = 30 \) GPa, \( I = \frac{bh^3}{12} = 5.33 \) m\(^4\); \( \sigma_s \) is strength of extension of main roof, and \( \sigma_s = 6 \) MPa. As a result, \( L = 7.62 \) m, which is the max-length of above-mentioned beam. \( M_0 \) and \( Q_0 \) are the bending moment and the shearing force at \( x = 0 \). The bending moment can be calculated as follow: \( M = EIy^* \).

**4.3 Discussion**

Above all, it can be conclude that mining method has large impact on dynamic disturbance induced by the main roof. Further analysis indicate that the structural characteristics of both far field and near field key strata under different mining methods lead to this difference.

Firstly, the structural characteristics of far field key strata under different mining methods give rise to different degrees of stress concentration on the coal seam as well as the main roof. The difference leads to different deflections of main roof. As shown in Fig. 6, the concentration coefficient increases with the increase of mining height. Then the deflection of main roof increase as well as the energy released (Fig. 13).

Secondly, different mining methods lead to different structural characteristics of near field key strata(main roof). Thus, the force condition at the end of the main roof changes. As shown in Fig. 8, the model in Fig. 8 (a) own a vertical upward force which lead to a longest weighting interval. The model in Fig. 8 (d) have no vertical forces which lead to a second longest weighting interval. The models in Fig. 8 (b), (c) own vertical downward forces and show a increasing law on the weighting interval when the forces decrease. Therefore, the evolution of the energy released is easy to understand. A vertical downward force is likely to snap the beam in tension urgently when it is still short. But vertical upward force is likely to prevent the fracture as long as possible.
Thus the weighting interval of the beam changes. Once the deflection and the weighting interval change, the energy released changes.

As can be seen, the main roof of a large cutting height workface release most energy (situation VI and VII). Then is the top slice of thick coal seam mining workface or the thin seam mining workface (situation II). The energy released under a top coal caving mining workface (situation IV and V), medium-thickness coal seam mining workface (situation III) decrease in order.

Beside, other factors have also been discussed. As shown in Fig.9 to Fig.12, the mining depth, the proportion coefficient, the tensile strength of the main roof, the main roof’s thickness have large impact on the deflection of the beam and energy released by the main roof and the composite beam. The elasticity modulus of the main roof, the blank space height in a voussior beam structure have little impact on the deflection and energy released.

6 Conclusions

(1) The accurate mechanical model which can take mechanical quality and force condition into account is needed to be developed to describe the dynamic disturbance under different mining methods. Considering the energy released by the loading strata above main roof, the energy released by composite beam effect should be taken into account, too.

(2) Due to the stress transfer of rock strata above the inferior key strata as well as the loading transfer of the cantilever part, the loading exerted on the clamped part of the cantilever beam seem a wave. Thus, a linear wave is used to describe the real wave. Then the deflection of the main roof and the composite beam can be calculated and then the energy of them contained.

(3) When the fully mechanized mining method is applied to mining a thin seam or a top slice of thick seam which mining height is relative low, the length of the hanging overburden is relative small; when the fully mechanized mining bottom slice method is applied to the panel; when the overburden would touch the gangues and be supported by the gangues soon after the coal being excavated, the top-coal caving mining the whole coal seam method is applied; when the abutment pressure distribute on the coal seam is larger than that of mining bottom slice or mining the top slice, fully mechanized large cutting height mining method is applied; when the abutment pressure distribute on the coal seam and the main roof is the largest of all the mining method.

(4) With the increase of the mining height, the concentration coefficient of static stress increase. Thus, the mining method can largely effect the concentration coefficient of static stress. The large cutting height mining have the max the concentration coefficient and the thin seam or the top slice mining have the min the concentration coefficient. Furthermore, with the increase of the bulking coefficient of the rock blocks, the concentration coefficient decreases.

(5) The proportion coefficient which reflect the stiffness can largely effect the deflection of the beam and then energy released; with the increase of the mining depth, the deflection of the beam increases and the energy released increases, too; the Elastic Modulus has little impact on the deflection and energy release and the proportion coefficient has largely impact.

(6) It can be conclude that mining method has large impact on dynamic disturbance induced by the main roof. Further analysis indicate that the structural characteristics of both far field and near field key strata under different mining methods lead to this difference. The proportion coefficient, the tensile strength of the main roof, the main roof’s thickness have large impact on the deflection of the beam and energy released by the main roof and the composite beam. The elasticity modulus of the main roof, the blank space height in a voussior beam structure has little impact on the deflection and energy released.
Data Availability All data used to support the findings of this study are included within the article, and there are not any restrictions on data access.

Conflicts of Interest The authors declare no conflicts of interest.

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