Stability Analysis of Rib Pillars in Highwall Mining Under Dynamic and Static Loads in Open-Pit Coal Mine

Haoshuai Wu  
China University of Mining and Technology

Yanlong Chen (chenyanlong@cumt.edu.cn)  
China University of Mining and Technology  
https://orcid.org/0000-0001-6771-5201

Haoyan Lv  
China University of Mining and Technology

Qihang Xie  
China University of Mining and Technology

Yuanguang Chen  
China University of Mining and Technology

Jun Gu  
China University of Mining and Technology

Research

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Stability analysis of rib pillars in highwall mining under dynamic and static loads in open-pit coal mine

Haoshuai Wu1 · Yanlong Chen1,* · Haoyan Lv2 · Qihang Xie2 · Yuanguang Chen2 · Jun Gu2

1 State Key Laboratory for Geomechanics and Deep Underground Engineering, China University of Mining and Technology, Xuzhou, 221116, China
2 School of Mechanics and Civil Engineering, China University of Mining and Technology, Xuzhou, 221116, China
* Correspondence: chenyanlong@cumt.edu.cn

Abstract The highwall miner can be used to mine the retained coal in the end slope of an open-pit mine. However, the instability mechanism of the reserved rib pillar under dynamic and static loads is not clear, which restricts the safe and efficient application of the highwall mining system. In this study, the load-bearing model of the rib pillar in highwall mining was established, the cusp catastrophe theory and the safety coefficient of the rib pillar were considered, and the criterion equations of the rib pillar stability were proposed. Based on the limit equilibrium theory, the limit stress of the rib pillar was analyzed, and the calculation equations of plastic zone width of the rib pillar in highwall mining were obtained. Based on the Winkler foundation beam theory, the elastic foundation beam model composed of the rib pillar and roof under the highwall mining was established, and the calculation equations for the compression of the rib pillar under dynamic and static loads were developed. The results show that with the increase of the rib pillar width, the total compression of the rib pillar under dynamic and static loads approximately decreases in an inverse function, and the compression of the rib pillar caused by static loads of the overlying strata and trucks has a decisive role. Numerical simulation and theoretical calculation were performed in this study. In the Numerical simulation, the coal seam with a buried depth of 122 m and a thickness of 3 m was mined by the highwall miner. According to the established rib pillar instability model of the highwall mining system, it is found that when the mining tunnel width is 3 m, the reasonable width of the rib pillar is at least 1.3 m, and the safety factor of the rib pillar is 1.3. The numerical simulation results are in good agreement with the results of theoretical calculation, which verifies the feasibility of the theoretical analysis of the rib pillar stability. The research results can provide an important reference for the stability analysis of rib pillars under highwall mining.

Keywords Open-pit coal mine · Dynamic and static loads · Highwall mining · Rib pillar · Catastrophe instability.

1 Introduction

At present, near-horizontal coal seams are mostly encountered in the large-scale open-pit coal mines under development in China, and the mining procedure of internal pressure relief in zones is widely adopted (Chen and Wu 2016; Wu et al. 2020; Chen et al. 2020). According to the traditional open-pit mining design theory, the transportation lines discharged by trucks in these large-scale open-pit mines are set on the two ends of the wall, and the formed end slope angle is less than the stable slope angle. As a result, a large number of coal resources are occupied by the end slope (Wang and Zhang 2019; Chen et al. 2020). With the continuous advancement of the inner dump and working slope, the coal occupied by the end slope will be re-buried by the inner dump. Due to the limitations of the current mining technology and mining equipment in China, it is difficult to conduct secondary mining in these mines (Wang et al. 2019; Pan et al.
Generally, a double lane inner row line of heavy-duty and no-load large mining trucks is set on the haulage bench of the end slope of the open-pit mine. For heavy-duty trucks, the truck weight plus load can reach 600 t, which brings a strong dynamic load and a great impact on the stability of the lower rib pillar (Wu et al. 2020; Chen et al. 2020). Therefore, when the highwall miner (Hood et al. 2020; Sasaoka et al. 2016; Chang et al. 2021) is used to mine the retained coal in the end slope, the load on the reserved rib pillar is the composite load superimposed by the strong dynamic load generated by mining trucks and the non-uniform static load generated by end slopes.

Wilson's two-zone constraint theory has been widely used in the load calculation of rib pillars in strip mining in China (Wilson 1973). By this method, the ultimate bearing capacity and actual load of rib pillars are calculated, and the safety coefficient of the rib pillar is calculated to evaluate the stability of the rib pillar. Lin'Kov (2001) calculated the strength at different positions in the core area by combing the strength of the core area in a rib pillar with the actual stress, and put forward a general equation for calculating the failure envelope of the long rib pillar. Pietruszczak and Mroz (1981) regarded the strike section of the goaf as a flat elliptical orifice in an infinite plate with uniformly distributed load acting on the boundary, and derived the stress calculation equation of any distance point between the rib pillar at the end of the orifice and the coal wall using the elastic fracture theory. Based on the cusp catastrophe theory of elastic thin plate, Mu et al. (2019) studied the critical conditions of roof and floor buckling. Xia et al. (2019) and Wang et al. (2021) explored the instability mechanism of the pillar based on cusp catastrophe theory. Aiming at the deformation characteristics of the surrounding rock, Zhang et al. (2019) proposed a calculation method based on cusp catastrophe theory. Yuan et al. (2019) investigated the surrounding rock system of the water-rich roadway in sandy-gravel stratum based on catastrophe theory, and put forward the instability criterion of the roadway in sandy-gravel stratum under seepage. Considering the cusp catastrophe theory and elastic thin plate theory, Ma et al. (2019) discussed the necessary and sufficient conditions for the instability of strip-supported rib pillars under two different constraints. Combining the Hoek-Brown failure criterion with the Mohr-Coulomb failure criterion, Wang et al. (2019) obtained the equation for calculating the width of strip-supported rib pillar, and analyzed the failure mechanism of strip-supported rib pillar and the factors affecting the width of strip-supported rib pillar in detail. Through the FLAC3D software, Porathur et al. (2014) and Wang et al. (2019) researched the slope stability under the conditions of different pillar widths and different adit widths in highwall mining of open-pit coal mines. Mo et al. (2018) quantitatively studied the influence of backfilling on rib pillar strength in highwall mining by using the FLAC2D software. Zhong and Ma (2020), He et al. (2021) researched the slope stability by using the ANSYS/LSDYNA software. From the 1950s to 1960s, the ideal elastic-plastic analytical solution of surrounding rock of axisymmetric circular roadway, namely Kastner equation, was derived (Obert and Duvall 1967; Jaeger and Cook 1978). Based on the stress balance theory of loose media and the stress differential equilibrium equation, Hou and Ma (1989) obtained the coal seam interface stress and the width of the stress limit equilibrium zone (plastic zone) of the coal body. On the basis of the elastic-plastic mechanics, Li et al. (2004) deduced the width of stress limit equilibrium zone of retained strip rib pillar using the stress balance differential equation and Coulomb criterion. Besides, the plastic zone width of the strip rib pillar was also deduced by using the complex function model of elastic theory, and then different theoretical equations were obtained. Tang et al. (2021) proposed a method of determining the critical buckling load of piles based on the beam-on nonlinear
Winkler foundation model. Sanches et al. (2020) carried out nonlinear finite element analysis on the dynamic characteristics of nonlinear Winkler foundation beam under moving load, calculated the critical velocity of moving load, and analyzed the influence of physical and geometric nonlinear characteristics of the system on the critical velocity.

Highwall mining has great practical value in terms of industrial policy and mining efficiency. However, there are little researches on highwall mining in China. Due to the different application conditions of the highwall mining system, different coal rock occurrence and geological conditions in China and foreign countries, it is difficult to ensure the rationality and reliability of rib pillars designed by empirical equation via analyzing the stability of supporting rib pillars. In this study, the instability mechanical model of strip-supported rib pillar in highwall mining was established, which provides a basis and foundation for the safe and efficient mining of retained coal in an open-pit mine by using highwall mining technology.

2 Instability mechanism of the rib pillar in highwall mining

2.1 Mechanical model of the rib pillar load-bearing

The external load of the strip-supported rib pillar mainly comes from the static load of overlying strata and the dynamic load caused by the driving of mining trucks. Due to the action of external load, a yield zone is formed on both sides of the rib pillar. According to the two-zone constraint theory proposed by Wilson (1973), from the peak value of the rib pillar stress to the boundary of the rib pillar (i.e. in the plastic zone), the stress of the rib pillar exceeds the yield stress and flows to the goaf.

As shown in Fig. 1, the load borne by the rib pillar includes two parts: (1) the static load of the overlying strata; (2) the dynamic load caused by the driving of trucks. The stress of the coal body in the plastic zone of the rib pillar does not exceed the yield stress, which conforms to the elastic law. This area is surrounded by the plastic zone and constrained by the plastic zone, which is called the elastic core zone of the rib pillar. According to the effective area theory, the elastic core zone of the rib pillar carries three kinds of load, including the static load of rock strata above the upper elastic core zone of the rib pillar, the load of the overlying strata evenly divided by adjacent rib pillars and the dynamic load caused by trucks.

For the dynamic loads generated by mining trucks, the following four factors should be considered:

(1) The running speed of the mining truck on the haulage bench of an open-pit mine is generally not more than 30 km/h. Therefore, the dynamic loads caused by the horizontal movement of the mining truck is ignored, and only the impact load caused by the uneven road surface of the mining truck is considered;

(2) Because the wheel diameter of a large mining truck is larger than the width of the rib pillar, the front and rear wheels of the mining truck will not act on the same rib pillar at the same time, that is, each rib pillar can only carry the front or
rear wheels of the mining truck;

(3) Commonly used mining trucks generally have 2 front wheels and 4 rear wheels. As shown in Fig. 2, under the full load, the load distribution of front and rear axles is approximately 1:2, that is, the specific pressure of wheel-to-ground is approximately equal and the wheel-to-ground contact area is approximately the same;

![Fig. 2 Calculation diagram of wheel-to-ground contact area during truck driving.](image)

(4) When the rear wheel of a fully-loaded mining truck acts directly above the rib pillar, the rib pillar bears the maximum external load. At this time, the wheel-to-ground contact area of the mining truck is calculated by \(a \times b\), where \(a\) is the length of the wheel-to-ground contact area and \(b\) is the wheel width. Combined with factor (1), the wheel-to-ground load can be simplified as a uniformly distributed static load, with a width of \(a\), the load value of \(q_0\) and the dynamic load coefficient of \(k_d\).

When the cutting width of the highwall miner is 2.9-3.7 m (Chen et al. 2013; Yin and Dong 2015), no caving occurs in the roof of the rib pillar roof. As shown in Fig. 1, it is assumed that the average thickness of the overlying strata is \(H\) and the unit weight is \(\gamma\), the width of the rib pillar is \(W_p\) and the width of the mining tunnel is \(W_m\), then the load borne by the rib pillar (in plane) is:

\[
P = \gamma H (W_m + W_p) + k_d q_0 a
\]  

(1)

where \(a_0\) is the strain of the rib pillar under load; \(E\) is the initial elastic modulus of the rib pillar.

Assuming that the width of the plastic zone on one side of the rib pillar is \(Y\) and the thickness of the coal seam is \(H_p\); in the plastic zone of the rib pillar with a total width of \(2Y\) or in the elastic core zone of the rib pillar with a width of \(W_p - 2Y\), the relationship between plastic zone load \(P_p\), elastic core zone load \(P_e\) and deformation \(u\) can be expressed by the following equation (2):

\[
P_p = \frac{2YEu}{H_p} e^{-\frac{u}{e_0}}, \quad P_e = \frac{(W_p - 2Y)Eu}{H_p}
\]  

(3)

where \(u_0\) is the compression of the rib pillar under load.

### 2.2 The rib pillar failure and instability model based on the cusp catastrophe theory

The strain energy \(V_1\) of the plastic zone of the strip-supported rib pillar, the elastic potential energy \(V_2\) of the elastic core zone of the strip-supported rib pillar and the gravity potential energy \(V_3\) of the overlying strata and the truck can be obtained from equations (1) respectively:

\[
V_1(u) = \frac{2YE}{H_p} \int_0^u \frac{u e^{-\frac{u}{e_0}}}{\gamma H (W_m + W_p)} du
\]  

(4)

\[
V_2(u) = \frac{E(W_p - 2Y)}{H_p} \int_0^u \frac{u}{\gamma H (W_m + W_p)} du
\]  

(5)

\[
V_3(u) = Pu = \left[\frac{\gamma H (W_m + W_p) + k_d q_0 a}{\gamma H (W_m + W_p) + k_d q_0 a}\right] u
\]  

(6)

The total potential energy of the roof-rib pillar system composed of rib pillar, overlying strata and truck can be expressed as:

\[
V(u) = V_1 + V_2 - V_3 = \frac{2YE}{H_p} \int_0^u \frac{u e^{-\frac{u}{e_0}}}{\gamma H (W_m + W_p)} du + \frac{E(W_p - 2Y)}{H_p} \int_0^u \frac{u}{\gamma H (W_m + W_p) + k_d q_0 a} du
\]  

(7)

Taking \(u\) as the state variable, the catastrophe theory is used for analysis. The first derivative of \(V(u)\) is taken and \(V(u) = 0\), then the equation of the equilibrium surface can be obtained:

\[
V'(u) = \frac{2YE}{H_p} e^{-\frac{u}{e_0}} + \frac{E(W_p - 2Y)}{H_p} u - \left[\frac{\gamma H (W_m + W_p) + k_d q_0 a}{\gamma H (W_m + W_p) + k_d q_0 a}\right] = 0
\]  

(8)
Equation (8) is derived further to obtain the equation:

\[ V(u) = \frac{2EY}{H_p u_0} u - \frac{u}{u_0} - 2 = 0 \]  

(9)

After solving equation (9), then:

\[ u = u_i = 2u_0 \]  

(10)

The equilibrium surface equation \( V(u) \) is expanded into a power series according to Taylor equation at \( u = u_i = 2u_0 \), and is taken to the cubic term. Then it can be simplified as:

\[
\frac{4EY \xi - (u - u_i)}{3H_p \xi} + \frac{2EY \xi (u - 2Y) - 1}{2Y} - \frac{(u - u_i)}{u_i} = 0
\]  

(11)

\[ P = \gamma H (W_m + W_p) + k_0 \xi \]  

(12)

The dimensionless quantity \( \xi \) is introduced as the state variable, \( p \) and \( q \) as the control variables, and let:

\[
\xi = \frac{u - u_i}{u_i}, \quad p = \frac{3}{2} (k_o - 1), \quad q = \frac{3}{2} (1 + k_o - \xi)
\]  

(13)

where \( k_o \) is the stiffness ratio, \( k_o = k_e/k_s \); \( k_e \) is the stiffness of medium in the elastic core zone of the rib pillar, \( k_s = E(W_p - 2Y)/H_p \); \( k_s \) is the stiffness of the medium in the plastic zone of rib pillar, \( k_s = 2EY \xi H_p \); \( t \) is defined as a parameter related to mining conditions, i.e. mining depth \( H \), mining width \( W_m \), rib pillar width \( W_p \) and unit weight \( \gamma \), the coal seam thickness \( H_p \) and relevant mechanical parameters of coal samples. Then equation (14) can be obtained as follows:

\[
k_o = k_e k_s, \quad \xi = \frac{(W_p - 2Y) e^2}{2Y}, \quad t = \frac{H_p e^2}{2EY u_i} P
\]  

(14)

By substituting equation (13) and equation (14) into equation (11), an equilibrium equation (with \( \xi \) as a state variable, \( p \) and \( q \) as control variables) can be obtained, which conforms to the standard form of cusp catastrophe:

\[
\xi^3 + p\xi + q = 0
\]  

(15)

By solving the simultaneous equation (15) and inflection point equation \( 3\xi^2 + p = 0 \), the bifurcation set equation can be obtained:

\[
\Delta = 4p^2 + 27q^2 = 0
\]  

(16)

By substituting equation (13) and equation (14) into the bifurcation set equation (16), the bifurcation set equation (17) of the cusp catastrophe (Chen et al. 2021; Dong et al. 2021) of the system can be obtained:

\[
\Delta = 2 \left[ \frac{(W_p - 2Y) e^2}{2Y} - 1 \right] + 9 \left[ 1 + \frac{(W_p - 2Y) e^2}{2Y} - \frac{H_p e^2}{4EY u_i} [\gamma H (W_m + W_p) + k_0 q \xi] \right]^2 = 0
\]  

(17)

2.3 Criterion equation of the rib pillar stability

The stress of the rib pillar \( \sigma_p \) can be obtained as:

\[
\sigma_p = \frac{P}{W_p} = \frac{\gamma H (W_m + W_p) + k_0 q \xi}{W_p}
\]  

(18)

According to the ultimate strength theory, the safety factor \( f \) of the rib pillar can be obtained from the ultimate stress \( \sigma_p \) of the rib pillar and stress \( \sigma_s \) borne by the rib pillar.

\[ f = \frac{\sigma_p}{\sigma_s} = \frac{\gamma H (W_m + W_p) + k_0 q \xi}{W_p}
\]  

(19)

Due to the difference in actual mining conditions and geological conditions of the highwall mining, the selection of the safety factor of the rib pillar is different. According to the previous studies of highwall mining, the safety factor of the rib pillar is generally greater than 1.3 (Chen et al. 2013; Zipf and Mark 2005).

As described in Chapter 2.2, to maintain the stability of the rib pillar in highwall mining, the two conditions must be met simultaneously to obtain the comprehensive criterion equation (20) for sudden instability of the rib pillar under highwall mining:

\[
\left\{ \begin{array}{l} \Delta > 0 \\ f > 1.3 \end{array} \right.
\]  

(20)

3 Analysis on influencing factors of the rib pillar stability

According to the equation (20), there are three main variables in the mechanical criterion of the rib pillar instability, including the plastic zone width \( Y \) of the rib pillar, the ultimate stress \( \sigma_p \) borne by rib pillar, and the compression \( u_0 \) of the rib pillar under external load.
3.1 Calculation of plastic zone width and ultimate stress of the rib pillar

Based on the limit equilibrium theory, it is assumed that the roof and floor of coal seams are consistent, and the compressive strength is greater than that of coal. Without considering the physical strength, the mechanical analysis model of the lower mining tunnel and surrounding rock in highwall mining is established (Gu et al. 2014). As shown in Fig. 3, in highwall mining, the mining tunnel width is \(W_m\), the rib pillar width is \(W_p\), the mining tunnel height is \(H_p\), and the coal seam buried depth is \(H\), the vertical stress of \(\sigma_0\) is \(\gamma H + [k_wq_0l(W_m + W_p)]\), the horizontal stress at infinity from the mining tunnel is \(\lambda \sigma_0\), side pressure coefficient \(\lambda = \mu / (1 - \mu)\), and \(\mu\) is the Poisson’s ratio of coal.

The model is bilaterally symmetrical along the central line of the mining tunnel and longitudinally symmetrical along the x-axis. A micro element in the plastic zone of the rib pillar is taken, as shown in Fig. 4. Because the plastic zone is the limit equilibrium zone, the average shear stress at the interface between roof and floor and coal seam \(\tau\) and vertical load \(\sigma_y\) meet the function:

\[
\tau = c_0 + \sigma_y \tan \phi_0
\]

where \(c_0\) and \(\phi_0\) are the cohesion and internal friction angle of the interface between coal seams and the roof and floor.

The equilibrium equation in the x-axis direction of the micro element is established and simplified as follows:

\[
\frac{\partial \sigma_x}{\partial x} - \frac{2\sigma_y \tan \phi_0 + c_0}{H_p} = 0
\]  

(22)

According to the Mohr-Coulomb yield criterion, the plastic zone of coal is in the limit equilibrium state, and the following equation can be obtained:

\[
\sigma_i = \frac{1 + \sin \varphi}{1 - \sin \varphi} \sigma_3 + \frac{2c \cos \varphi}{1 - \sin \varphi}
\]

(23)

The vertical stress and horizontal stress of micro element are the main stress. In equation (23), \(c\) and \(\varphi\) are cohesion and internal friction angle of coal body, and \(\sigma_1 = \sigma_x\), \(\sigma_3 = \sigma_y\).

In equation (23), \(X\) is differentiated and \(A = (1 + \sin \varphi)/(1 - \sin \varphi)\), then boundary conditions \(\sigma_3 = 0\) are substituted. Given that \(N_1 = (2c \cos \varphi)/(1 + \sin \varphi)\), if \(x \in [0,Y]\), the vertical stress \(\sigma_y^p\) and horizontal stress \(\sigma_x^p\) of micro elements in the plastic zone can be obtained:

\[
\begin{align*}
\sigma_y^p & = \left\{ \frac{N_1 A + \frac{c_0}{\tan \phi_0}}{H_p} \right\} e^{\frac{2A \tan \phi_0}{H_p} x} - \frac{c_0}{\tan \phi_0} \\
\sigma_x^p & = \left\{ N_1 + \frac{c_0}{A \tan \phi_0} \right\} e^{\frac{2A \tan \phi_0}{H_p} x} - 1
\end{align*}
\]

(24)

The vertical ultimate stress \(\sigma_y^p\) of the rib pillar can be obtained from the equation (24):

\[
\sigma_y^p \bigg|_{x=r} = \frac{2c \cos \varphi}{1 - \sin \varphi} \frac{1}{\tan \phi_0} e^{\frac{2(1 + \sin \varphi) tan \phi_0}{(1 - \sin \varphi) H_p}} - \frac{c_0}{\tan \phi_0}
\]

(25)
Combined with the principle of stress balance, after the mining tunnel is excavated, the load originally borne by the coal body in the mining tunnel section is transferred to the rib pillars on both sides of the mining tunnel. Assuming that the vertical stress and horizontal stress of micro elements are equal to the average stress distributed along with the coal seam thickness, there are:

\[
\frac{1}{2}W_0\sigma_0 = \int^y_0 (\sigma^+ - \sigma^-) \, dx + \int^h_y (\sigma^+ - \sigma^-) \, dx \tag{26}
\]

The equation (26) is simplified, and let \(X=(2Y\tan\phi_0)/H_p\), then equation (27) can be obtained:

\[
q_1(x) = kb_2 y(x) \tag{29}
\]

If the influence of shear force on beam deflection is not considered, according to the balance condition of the force, let \(\alpha=[kb/4E_1I]^{1/4}\) and \(\alpha x\) is used to replace \(x\), then:

\[
d^2y(x) + 4y(x) = \frac{4}{kb_2}q(\alpha x) \tag{30}
\]

The homogeneous solution of the differential equation (30) of the deflection curve can be obtained by introducing hyperbolic function:

\[
y(x) = B_1\cosh(\alpha x)\cos(\alpha x) + B_2\sinh(\alpha x)\cos(\alpha x) + B_3\sinh(\alpha x)\sin(\alpha x) + B_4\cosh(\alpha x)\sin(\alpha x) \tag{31}
\]

According to the boundary conditions of the beam on the elastic foundation,

\[
\begin{aligned}
B_1 &= y_0, \\
B_2 &= -\frac{1}{4}\alpha^2 E_1 I Q_0, \\
B_3 &= -\frac{1}{2}\alpha E_1 I Q_0, \\
B_4 &= -\frac{1}{2}\alpha E_1 I M_0
\end{aligned} \tag{32}
\]

Equation (32) is substituted into equation (31) to obtain:

\[
y(x) = y_0 + \frac{1}{2\alpha} \phi_1(x) + \frac{1}{2\alpha^3} \phi_2(x) M_0 + \frac{2\alpha^2}{kb_2} \phi_3(x) - Q_0 \frac{\alpha}{kb_2} \phi_4(x) \tag{33}
\]

and

\[
\begin{aligned}
\phi_1(x) &= \cosh(\alpha x)\cos(\alpha x) \\
\phi_2(x) &= \cosh(\alpha x)\sin(\alpha x) + \sinh(\alpha x)\cos(\alpha x) \\
\phi_3(x) &= \sinh(\alpha x)\sin(\alpha x) \\
\phi_4(x) &= \cosh(\alpha x)\sin(\alpha x) - \sinh(\alpha x)\cos(\alpha x)
\end{aligned} \tag{34}
\]

As shown in Fig. 6, the additional term caused by uniformly distributed load \(q(x)=q_0\) is introduced, equation (35) can be obtained:
3.2.2 Rib pillar compression under dynamic loads of the truck

Since the compression of the rib pillar under the dynamic loads of a fully-load truck is greater than that of a no-load truck, only the compression of the rib pillar under the dynamic load of a fully-loaded truck is discussed. As shown in Fig. 7, the rib pillar group between two permanent rib pillars is taken as the research object along the direction of the haulage bench in the end slope.

As shown in Fig. 8, the coordinate system yoz is established, the y-axis is established along the horizontal direction, and the z-axis is established along the vertical direction. The boundary conditions of the calculation model are:
\[
\begin{align*}
\left[ \frac{\partial z}{\partial y} \right]_{y=0, h} &= 0 \\
\left[ \frac{\partial \theta}{\partial y} \right]_{y=0, h} &= 0
\end{align*}
\]

The dynamic loads of a truck are further simplified. Assuming that the compression generated on the rib pillar in the middle of the rib pillar group (near y=0) does not decay when the truck is driving, the compression generated by dynamic loads of a truck on a certain rib pillar can be simplified as the sum of the compression generated by the static load between the truck and the rib pillar at different distances, and this compression is defined as \( u_2 \).
coefficient is \( k = [E(W_p-2Y)]/[H_p(W_m+W_p)] \); the height of the roof is \( h \), the length is \( 2l_1 \), the width of the roof is unit one, the elastic modulus is \( E_1 \), and the elastic standard value is \( \alpha = [3k_y/(E_1l_1h^3)]^{1/4} \). The interval of the uniformly distributed load is \( y \in [y_1,y_2] \), \( y \in [y_3,y_4] \). By substituting the boundary conditions (36) into equation (35), the initial parameter \( z_0 \), \( \theta_0 \), \( M_0 \) and \( Q_0 \) can be obtained by solving equation. Subsequently, the calculation equation (37) of coal seam compression \( z(y) \) along the y-direction of the coordinate axis can be obtained:

\[
\begin{align*}
\frac{d}{dy} \left( \begin{array}{c}
z_0 (q) \\
\theta_0 (q) \\
M_0 (q) \\
Q_0 (q)
\end{array}\right) = \frac{1}{k} \left( \begin{array}{c}
\frac{2}{\alpha} \phi_2(y) - M_0 \\
\phi_2(y) - Q_0 \\
\frac{2}{\alpha} \phi_2(y) - M_0 \\
\phi_2(y) - Q_0
\end{array}\right) \\
\frac{d}{dy} \left( \begin{array}{c}
z_0 (q) \\
\theta_0 (q) \\
M_0 (q) \\
Q_0 (q)
\end{array}\right) = \frac{1}{k} \left( \begin{array}{c}
\frac{2}{\alpha} \phi_2(y) - M_0 \\
\phi_2(y) - Q_0 \\
\frac{2}{\alpha} \phi_2(y) - M_0 \\
\phi_2(y) - Q_0
\end{array}\right)
\end{align*}
\]

The obtained \( z(y) \) curve is integrated on the interval of \( y \in [-l_1,l_1] \). Finally, the compression \( u_2 \) of the rib pillar caused by the dynamic loads of the fully-loaded truck is obtained:

\[
u_2 = \int_{-l_1}^{l_1} z(y) dy
\]

### 3.3 Calculation of the rib pillar compression under the combined static load of overlying strata and truck static

The loads of overlying strata that deform the elastic foundation are \( q_1, q_2, \ldots, q_6 \) \((n \in \mathbb{N}^+)\), corresponding to the coordinate intervals \( x \in [x_1,x_2], x \in [x_2,x_3], \ldots, x \in [x_m,x_m+1] \). The loads of the truck that deform the elastic foundation are \( q_{n+1}, q_{n+2}, \ldots, q_{n+m} \) \((n \in \mathbb{N}^+ \) and \( m \) is a multiple of 4\), corresponding to the coordinate interval \( x \in [x_{m+1},x_{m+2}], x \in [x_{m+2},x_{m+3}], \ldots, x \in [x_{2m+1},x_{2m+2}], x \in [x_{2m+2},x_{2m+3}], \ldots, x \in [x_{2m+n},x_{2m+n+1}] \), where \( q_{2m+1}, q_{2m+3}, q_{2m+5}, \ldots \), \( q_{2m+n-3}, q_{2m+n-1} \) are the static loads of the rear wheels of the truck under no-load; \( q_{2m+2}, q_{2m+4}, q_{2m+6}, \ldots \), \( q_{2m+n-2}, q_{2m+n} \) are the static load of the rear wheel of the truck when it is fully loaded. **Fig. 9** shows the established coordinate system \( xoz \).

---

**Fig. 9** Calculation model of the rib pillar compression under the static load of overlying strata and the truck.

As shown in **Fig. 9**, assuming that the width of the stope is \( W_m \), the height is \( H_p \), the width of the supporting rib pillar is \( W_p \), the elastic modulus is \( E \), the width of the plastic zone is \( Y \), the height of the roof is \( h \), the length is \( l_2 \), the elastic modulus is \( E_1 \), then the width of the roof is \( b_1=W_m+W_p \), and the width of the elastic core area of the rib pillar is \( b_2=W_p-2Y \).

The foundation coefficient \( k \) is defined as:

\[
k = \frac{E}{H_p}
\]

The elastic index value of roof (beam) \( \alpha \) is defined as:
\[ \alpha = \sqrt{\frac{3k(W_0 - 2Y)}{E_h h^3 (W_m + W_p)}} \] (40)

As shown in Fig. 9, the boundary conditions of the model are:
\[
\begin{align*}
[z(x)]_{x=0} &= 0, \quad [M(x)]_{x=0} = 0 \\
[\theta(x)]_{x=0} &= 0, \quad [Q(x)]_{x=0} = 0
\end{align*}
\] (41)

By substituting the boundary conditions (41) into equation (35), the initial parameter \( z_0 \) and \( \theta_0 \) can be obtained by solving the equations. Thus, the coal seam compression \( z(x) \) along the coordinate axis can be obtained:
\[ z_i(x) = z_0 \phi_i(x) + \theta_0 \frac{1}{2\alpha} \varphi_2(x) + \frac{1}{k b_2} \sum_{i=1}^{n} \left[ q_i \left( \phi_i(x) - \phi_i(x) \right) \right] + \frac{1}{k b_2} \sum_{i=1}^{m} \left[ q_{i+n} \left( \phi_i(x) - \phi_{i+n} \right) \right] \]

By analyzing the \( z(x) \) curve, the maximum compression \( u_{3_{\text{max}}} \) and corresponding coordinate \( x \) of the rib pillar under the static load of overlying strata and truck can be obtained:
\[ u_{3_{\text{max}}} = z(x) \] (43)
To sum up, the total compression \( u_0 \) of the rib pillar under dynamic and static loads superposition is equal to the sum of the rib pillar compression \( u_2 \) generated by dynamic loads of a truck and the rib pillar compression \( u_3 \) generated by the static load of overlying strata and truck, that is:

\[
u_0 = u_2 + u_3\quad (44)
\]

4 Case study

Fig. 10 shows the schematic diagram of the end slope of an open-pit mine in highwall mining. The average thickness of the coal seam closest to the surface is 3 m and the buried depth is 122 m. After open-pit mining, the width of the compressed coal seam in the end slope is about 190 m. The physical and mechanical parameters of coal and rock strata of end slope are shown in Table 1.

Fig. 11a shows the schematic diagram of the wheel-to-ground contact area when the mining truck is fully loaded (600 t). According to the calculation of design parameters, the bearing capacity of each wheel is 100 t. Figure 11b shows the schematic diagram of the wheel-to-ground contact area when the mining truck is unloaded (237 t). Each wheel of the front wheel carries 54.5 t, and each wheel of the rear wheel carries 32 t.

![Section view of end slope in an open-pit mine.](image)

**Table 1** Physical and mechanical parameters of coal and rock strata of end slope.

| Lithology            | Depth (m) | Thickness (m) | \( \gamma \) (kN·m\(^{-3}\)) | \( E \) (MPa) | \( \mu \) | \( c \) (MPa) | \( \phi \) (°) |
|----------------------|-----------|---------------|-------------------------------|---------------|--------|--------------|-------------|
| Loess                | 30        | 30            | 19.6                          | 15            | 0.42   | 0.085        | 12          |
| Weathered sandstone  | 44        | 14            | 23.0                          | 2000          | 0.36   | 2.500        | 38          |
| Sandstone 1          | 74        | 30            | 23.8                          | 4200          | 0.32   | 3.000        | 39          |
| Mudstone             | 98        | 24            | 24.9                          | 2800          | 0.34   | 2.000        | 38          |
| Siltstone 1          | 110       | 12            | 23.2                          | 4600          | 0.32   | 3.500        | 36          |
| Sandstone 2          | 122       | 12            | 23.8                          | 4000          | 0.30   | 4.000        | 40          |
| Coal seam            | 125       | 3             | 14.4                          | 1000          | 0.38   | 1.620        | 36          |
| Shale 1              | 140       | 15            | 24.5                          | 4400          | 0.33   | 3.800        | 42          |
| Siltstone 2          | 155       | 15            | 26.0                          | 4800          | 0.32   | 5.000        | 38          |
| Shale 2              | 165       | 10            | 25.8                          | 3500          | 0.35   | 5.000        | 38          |
When the highwall miner is used to recover the retained coal in the end slope of the open-pit mine, the mining height and mining width are 3 m. The width of the rib pillar is designed by using the stability model of the lower rib pillar of highwall mining established in Chapter 2.

According to the established rib pillar instability model based on the cusp catastrophe theory, the plastic zone width of the rib pillar, the ultimate stress of the rib pillar and the compression of the rib pillar are calculated respectively. The reasonable rib pillar width $W_p$ is determined by analyzing the criterion values $\Delta$ of catastrophe instability of rib pillars with different widths and the safety factor value $f$ of the rib pillar.

**4.1 Calculation of plastic zone width of the rib pillar**

The plastic zone width of the rib pillar includes the sum of the plastic zone width caused by static load (slope) and the plastic zone width caused by dynamic load (truck). The No. 1 haulage bench is taken as an example. According to Table 1, the cohesion $c$ of the coal body and the cohesion $c_0$ of the interface between the coal seam and the roof and floor are set as 1.62 MPa; the friction angle $\phi$ in the coal body and the internal friction angle $\phi_0$ at the interface with roof and floor are set as 36°; the mining tunnel width is $W_m=3$ m, and the mining tunnel height is $H_p=3$ m; the dynamic load coefficient is $k_d=1.2$, and the static load is $q_0=1.8$ MN/m when a truck is fully loaded; the width of the uniformly distributed static load is $a=0.44$ m; the vertical stress for No. 1 haulage bench is $\gamma H=2491.6$ kPa. The plastic zone width $Y$ of the rib pillar with different pillar widths $W_p$ beneath the No. 1 haulage bench can be obtained by solving equation (27) and equation (28), as shown in Fig. 12.

**Fig. 11** Schematic diagram of the wheel-to-ground contact area. (a) Full load; (b) No load.

**Fig. 12** The plastic zone width of the rib pillar with different pillar widths beneath the No. 1 haulage bench.

As shown in Fig. 12, for the rib pillar directly below the No. 1 haulage bench, the plastic zone width $Y$ on both sides of the rib pillar gradually decreases with the increase of the width $W_p$ of the rib pillar. When the pillar width $W_p$ increases from 0.54 m to 3.00 m, the pillar plastic zone width $Y$ decreases from 0.269 m to 0.260 m, decreasing by 3.3%. The plastic zone width $Y$ of the rib pillar decreases linearly.

**4.2 Calculation of the rib pillar compression**

**4.2.1 Compression of the rib pillar under dynamic loads of the truck**

Along the direction of a mining tunnel, the rib pillar is equivalent to the elastic foundation. As the result of the
highwall mining, the load above the elastic foundation is redistributed. When the fully-loaded truck and unloaded truck meet on each two-lane haulage bench at the same time, then the maximum static load is generated by trucks.

As shown in Fig. 8, one permanent isolated rib pillar is reserved in every ten rib pillars, and the width of the isolated rib pillar is 12 m; then half the length of the model is reserved in every ten rib pillars, and the width of the isolated rib pillar reserved width is substituted into the foundation coefficient equation (35), so as to obtain the coal seam compression of static loads of overlying strata and truck

The loads of overlying strata that deform the elastic foundation are \( q_1, q_2, \ldots, q_7 \), and the loads of the truck that deform the elastic foundation are \( q_8, q_9, \ldots, q_{23} \), therefore, \( n=7, m=16 \) in the equation (42). The overlying strata load at all levels can be expressed by the following equation (45):

\[
q_1 = 378.4(3 + 2Y) \text{kN/m}, \quad x \in [0, 40] \text{ m} \\
q_2 = 763.2(3 + 2Y) \text{kN/m}, \quad x \in [40, 50] \text{ m} \\
q_3 = 1161.6(3 + 2Y) \text{kN/m}, \quad x \in [50, 90] \text{ m} \\
q_4 = 1518.6(3 + 2Y) \text{kN/m}, \quad x \in [90, 100] \text{ m} \\
q_5 = 1875.6(3 + 2Y) \text{kN/m}, \quad x \in [100, 140] \text{ m} \\
q_6 = 2197.6(3 + 2Y) \text{kN/m}, \quad x \in [140, 150] \text{ m} \\
q_7 = 2491.6(3 + 2Y) \text{kN/m}, \quad x \in [150, 190] \text{ m}
\]

The static load of the unloaded truck is \( q_8=\ldots=q_{23}=307.2 \text{kN/m} \), corresponding to interval \( x \in [5.675,8.175] \text{ m}, \quad x \in [11.825,14.325] \text{ m} , \quad x \in [55.675,58.175] \text{ m} , \quad x \in [61.825,64.325] \text{ m} , \quad x \in [105.675,108.175] \text{ m} , \quad x \in [111.825,114.325] \text{ m} , \quad x \in [155.675,158.175] \text{ m}, \quad x \in [161.825,164.325] \text{ m} \).

The static load of a fully-loaded truck is \( q_8=\ldots=q_{23}=960.0 \text{kN/m} \), corresponding to interval \( x \in [25.675,28.175] \text{ m}, \quad x \in [31.825,34.325] \text{ m} , \quad x \in [75.675,78.175] \text{ m} , \quad x \in [81.825,84.325] \text{ m} , \quad x \in [125.675,128.175] \text{ m}, \quad x \in [131.825,134.325] \text{ m} , \quad x \in [175.675,178.175] \text{ m}, \quad x \in [181.825,184.325] \text{ m} \).

The parameter setting is as follow: the roof length is \( l_1=500 \text{ m} \), the roof height is \( h=12 \text{ m} \), the roof elastic modulus is \( E_1=4 \text{ GPa} \), the mining tunnel height is \( H_p=3 \text{ m} \), the mining width is \( W_m=3 \text{ m} \), and the foundation coefficient is \( k=1/3 \text{ GPa} \). As shown in Fig. 9, the boundary conditions of the mechanical model are shown in equation (41). By substituting the boundary conditions (41) into the equation (42), the coal seam compression \( z(x) \) along the \( x \)-direction, the maximum compression \( u_2 \) of the rib pillar under the static load of overlying strata and truck and the corresponding coordinate \( x \) is obtained.
As shown in Fig. 14, with the increase of the rib pillar width, the compression of the rib pillar under static load approximately decreases in inverse function. When the rib pillar width $W_p$ increases from 0.54 m to 0.80 m, the position of the maximum compression $u_3$ of the rib pillar decreases sharply from $x=12942.73$ mm to $x=99.20$ mm. When the rib pillar width $W_p$ continues to increase to 3.00 m, the position of $u_3$ decreases gently to $x=11.16$ mm.

As shown in Fig. 15, with the increase of the rib pillar width $W_p$, the position of the maximum compression $u_3$ of the rib pillar gradually shifts to the position of maximum buried depth of the rib pillar. When the rib pillar width $W_p$ increases from 0.54 m to 0.70 m, the position of maximum compression $u_3$ of the rib pillar shifts sharply from $x=129.00$ m (below the No. 2 haulage bench) to $x=157.25$ m (below the No. 1 haulage bench); When the rib pillar width $W_p$ continues to increase to 3.00 m, the position of maximum compression $u_3$ of the rib pillar slowly shifts from $x=157.25$ m (below the No. 1 haulage bench) to $x=162.75$ m (below the No. 1 haulage bench).

4.2.3 Compression of the rib pillar under superposition of dynamic and static loads

By analyzing the compression curve $z(x)$ of the rib pillar below No. 1 haulage bench ($x \in [150,190]$ m) under static load, it can be obtained that when the rib pillar width $W_p \in [0.54,0.58]$ m, the curve $z(x)$ decreases monotonically in the interval, then the maximum compression of the rib pillar below the No. 1 haulage bench under static load occurs at the position of $x=150$ m; When the rib pillar width $W_p \in [0.54,3.00]$ m, the curve $Z(x)$ first increases in the interval, reaches the peak and then decreases.

The total compression $u_0$ of the rib pillar under dynamic and static loads superposition is equal to the sum of the rib pillar compression $u_2$ generated by dynamic loads of the truck and the rib pillar compression $u_3$ generated by static loads of overlying strata and the truck, i.e. $u_0 = u_2 + u_3$. Moreover, the maximum compression of the rib pillar generated by dynamic loads of the truck is located directly below the contact between the wheel and the ground, that is, for No. 1 haulage bench, the rib pillar compression $u_2$ generated by dynamic loads of the truck has a superposition effect with the rib pillar compression $u_3$ generated by static loads of overlying strata and truck only at $x \in [155.675,158.175]$ m, $x \in [161.825,164.325]$ m, $x \in [175.675,178.175]$ m, and $x \in [181.825,184.325]$ m. The results are shown in Fig. 16.
From Fig. 16, it is concluded that with the increase of the rib pillar width, the total compression $u_0$ of the rib pillar approximately decreases in an inverse function. When the rib pillar width $W_p$ increases from 0.54 m to 0.80 m, the total compression $u_0$ under the No. 1 haulage bench decreases sharply from 12471.42 mm to 99.20 mm. When the rib pillar width $W_p$ continues to increase to 3.00 m, the total compression $u_0$ decreases gently to 11.16 mm.

The curve shown in Fig. 16 is basically consistent with that in Fig. 14. It can be seen that for the rib pillar directly below the No. 1 haulage bench, the rib pillar compression $u_2$ generated by dynamic loads of the truck is much smaller than the compression $u_3$ generated by static loads of overlying strata and truck. The rib pillar compression $u_3$ generated by static loads of overlying strata and truck plays a decisive role in the total rib pillar compression $u_0$ below the No.1 haulage bench.

4.3 Verification of the rib pillar stability criterion equations

4.3.1 Criterion value of the rib pillar stability

When the rib pillar width $W_p$ takes different values ($W_p \in [0.54,3.00]$ m), the calculated plastic zone width $Y$ of the rib pillar and the total compression $u_0$ of the rib pillar are substituted into equation (17), then criterion values $\Delta$ under different rib pillar widths can be obtained. The calculation results are shown in Fig. 17.

As shown in Fig. 17, the criterion value $\Delta$ sharply increases with the gradual increase of the rib pillar width $W_p$. When the rib pillar width $W_p$ increases from 0.54 m to 3.00 m, the criterion value $\Delta$ increases from 7 to 80065 in an approximate power function.

4.3.2 Ultimate stress and safety factor of the rib pillar

When the rib pillar width takes different values, the calculated plastic zone width $Y$ of the rib pillar and the total compression $u_0$ of the rib pillar can be substituted into equation (18) and equation (19). The ultimate stress $\sigma_p$ and safety factor $f$ under different rib pillar widths can be obtained, and the calculation results are shown in Fig. 18 and Fig. 19.
As shown in Fig. 18 and Fig. 19, with the increase of the rib pillar width, the ultimate stress of the rib pillar under No. 1 haulage bench approximately decreases linearly, and the safety factor of the rib pillar approximately increases linearly. When the rib pillar width \( W_p \) increases from 0.54 m to 3.00 m, the ultimate stress of the rib pillar gradually decreases from 11.965 MPa to 11.733 MPa, and the safety factor of the rib pillar increases from 0.66 to 2.21. The ultimate stress of the rib pillar decreases slightly, with a reduced rate of 1.9%, indicating that the ultimate stress is less affected by the change of the rib pillar width. The safety factor of the rib pillar increases greatly, with a growth rate of 234.8%, which is greatly affected by the change of the rib pillar width.

### 4.4 Analysis on reasonable reserved width of the rib pillar

Combined with Fig. 17 and Fig. 19, the criterion value \( \Delta \) of the rib pillar under the No. 1 haulage bench and statistical chart of the safety factor \( f \) can be obtained. According to the crust catastrophe instability model of rib pillars in highwall mining, if the rib pillar remains stable, criteria value \( \Delta > 0 \) is required. When the safety factor of the rib pillar \( f > 1.3 \) is taken, equation 46 can be obtained by solving the simultaneous equations of equation (20), equation (25), equation (27) and equation (28):

\[
W_p > 1.269 \text{ m}
\]  
(46)

Based on the above calculation, the rib pillar width under the No. 1 haulage bench is at least 1.3 m.

Based on the calculation of the rib pillar width under No. 1 haulage bench, when the width of rib pillar is \( W_p = 1.3 \text{ m} \), the safety factor \( f \) and criterion value \( \Delta \) of No. 1, 2, 3 and 4 haulage benches are checked, and the results are shown in Table 2.

### Table 2 Verification results of different haulage benches.

| Number of haulage bench | Plastic zone width of rib pillar \( Y \) (m) | Criterion value \( \Delta \) | Safety factor \( f \) |
|-------------------------|------------------------------------------|-----------------------------|----------------------|
| 1                       | 0.266                                    | 2042>0                     | 1.32>1.30            |
| 2                       | 0.214                                    | 6177>0                     | 1.52>1.30            |
| 3                       | 0.148                                    | 29735>0                    | 1.99>1.30            |
| 4                       | 0.068                                    | 512705>0                   | 3.79>1.30            |

Based on the calculation of No. 1-4 haulage benches, the width of rib pillar under this mining condition is at least 1.3 m.

### 4.5 Verification of numerical simulation by the ANSYS/LS-DYNA

Referring to the dimensions and physical and mechanical parameters of the end slope model shown in Fig. 10 and Table 1, the end slope model in Fig. 20 is established in the ANSYS/LS-DYNA, in which the slope angle of the loess layer is 55°, and the slope angle of other rock layers is 70°. A permanently isolated rib pillar is reserved in every ten strip supporting rib pillars. The mining tunnel is 3 m high, 3 m wide and 190 m long. The rib pillar is 190 m long, 1.3 m wide and 3 m high. The cross-section is stretched 58 m forward along the z-axis, and 11 cuboids as mining tunnels are reserved.

In order to eliminate the influence of boundary conditions
and reduce the calculation amount of the model, two rib pillars in the middle of the rib pillar group are taken as the main research objects and the mesh refinement is carried out, as shown in Fig. 21. The grid division of other strata is shown in Fig. 22. After the initial in-situ stress is balanced, the lifeland-death unit command is used to delete the grid of the mining tunnel (Fig. 23).

As shown in Fig. 24, a moving load on each haulage bench is applied, and the load of a truck is simplified into four-point loads. The load parameters are set referring to Chapter 4, and the load moving speed is 30 km/h.

![Fig. 20 Global view of end slope.](image1)

![Fig. 21 Coal seam modeling and local mesh refinement. (a) A local enlarged drawing of reserved life-and-death unit area of coal seams; (b) coal seam meshing.](image2)

![Fig. 22 Strata meshing. (a) The rock strata where the haulage bench is located; (b) transition strata; (c) the rock strata below the coal seam.](image3)

![Fig. 23 Meshing after highwall mining.](image4)

![Fig. 24 Schematic diagram of mesh division and dynamic load application of haulage bench.](image5)

After entering the ANSYS post-processor, the calculation results of the last step are read, and the unit after end slope
mining is selected. As shown in Fig. 25, the end slope does not produce an obvious plastic zone, so the slope is in a stable state under this mining condition. Due to the symmetry of the model, the unit belonging to the rib pillar group in the most middle part is further selected. As shown in Fig. 26, the rib pillar does not produce an obvious plastic zone at the shallow buried depth, but an obvious plastic zone can be seen at the deeply buried position (below the No. 1 haulage bench). The section diagram at the plastic strain peak of the rib pillar node is obtained by enlarging the section in the middle red frame area of Fig. 26. The plastic area of the rib pillar is not connected, and the width of the plastic area is about 0.26 m. The results are in good agreement with the theoretical calculation, which verifies the feasibility of the proposed theoretical calculation.

5 Conclusions

In this study, the difficulty in mining the retained coal in the end slope of an open-pit mine was taken as the research object; the stress distribution, energy evolution mechanism and instability disaster mechanism of the rib pillar under the superposition of the dynamic loads of the truck in the large-scale open-pit and the non-uniform static load of the end slopes were comprehensively considered. Based on the catastrophe theory, energy theory and rock mass mechanics, the mechanical analysis and numerical simulation were performed, the instability disaster mechanism of the rib pillar under dynamic and static loads in highwall mining system was comprehensively studied, and the design method of the rib pillar width in highwall mining was put forward. The main research results are as follows:

(1) According to the stress characteristics of the rib pillar in highwall mining, the cusp catastrophe theory and the requirements of rib pillar safety coefficient are considered, a comprehensive criterion for predicting the rib pillar stability is established. The comprehensive criterion is mainly determined by three factors: the plastic zone width of the rib pillar, the ultimate stress of the rib pillar and the corresponding compression of the rib pillar under external load.

(2) According to the limit equilibrium theory, the limit stress of the rib pillar is analyzed, and the calculation equation of the plastic zone width of the rib pillar on both sides of the mining tunnel is obtained. The results show that the plastic...
zone width of the rib pillar is determined by three factors: the mining height, the ratio of vertical stress peak to horizontal stress at the elastic-plastic boundary, and the internal friction angle between coal seam and roof and floor interface. Based on the Winkler foundation beam theory, an elastic foundation beam model composed of the rib pillar and roof under highwall mining is established, and the calculation equation of compression of the rib pillar under load is obtained.

(3) With the increase of the rib pillar width, the plastic zone width of the rib pillar decreases linearly; under the action of dynamic and static loads, the total compression of the rib pillar decreases in the form of an inverse function. In the total compression of the rib pillar, the compression of the rib pillar caused by static loads of overlying strata and truck plays a decisive role.

(4) Taking the actual mining conditions of the open-pit mine as the engineering background, the 3 m thick coal seam with a buried depth of 122 m is mined by the highwall miner through the numerical simulation. According to the established rib pillar instability model of the highwall mining system, a theoretical calculation is performed. The results show that when the mining tunnel width is 3 m, the reasonable width of the rib pillar is at least 1.3 m, and the safety factor of the rib pillar is 1.3. Through the verification of the numerical simulation test via the ANSYS/LS-DYNA, the theoretical calculation results are in good agreement with the numerical simulation results.

Declarations

Authors' contributions All authors contributed to the study conception and design. Conceptualization were performed by Haoshuai Wu and Yanlong Chen. Methodology were performed by Haoyan Lv and Yuanguang Chen. Data curation was performed by Qihang Xie and Jun Gu. The first draft of the manuscript was written by Haoshuai Wu and Yanlong Chen. All authors have read and agreed to the published version of the manuscript.

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References

Chang QL, Sun XK and Dong XJ et al (2021) Stability analysis of cemented paste backfill false roof in highwall mining: a case study. Desalination Water Treat 219: 96-102. http://doi.org/10.5004/dwt.2021.26781

Chen X, Tang MG and Tang CA (2021) Effect of confining pressure on the damage evolution and failure behaviors of intact sandstone samples during cyclic disturbance. Rock Mech Rock Eng. http://doi.org/10.1007/s00603-021-02672-z

Chen YL and Wu HS (2016) Catastrophe instability mechanism of rib pillar in open-pit highwall mining. J China Univ Min Technol 45(5): 859-865. http://doi.org/10.13247/j.cnki.jcumt.000557

Chen YL, Wu HS and Pu H et al (2020) Investigations of damage characteristics in rock material subjected to the joint effect of cyclic loading and impact. Energies 13(9): 2154. http://doi.org/10.3390/en13092154

Chen YL, Shimada H and Sasaoka T et al (2013) Research on exploiting residual coal around final end-walls by highwall mining system in China. Int J Min Recla Env 27(3): 166-179. http://doi.org/10.1080/17480930.2012.678768

Dong HY, Liu XG and Zhu WC (2021) Experimental and theoretical study of shear instability of rock joints in the direct shear test. Int J Geomech 21(3): 04021004. http://doi.org/10.1061/(ASCE)GM.1943-5622.0001943

Gu SC, Fan Q and Chen X (2014) A calculation method of plastic zone width for rectangular coal roadway. Saf Coal Mines 45(9): 24-27+31. http://doi.org/10.13347/j.cnki.mkaq.2014.09.007

He L, Zhong DW and Liu YH et al (2021) Prediction of bench
