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Periodic Fracture Model and Control of Hard Roof of Thin Coal Seam Short-wall Face: A Case Study of Zhuzhuang Coal Mine

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Abstract

The periodic fracture of the hard roof above the working face is the key influencing factor of ground pressure management in the underground exploitation of coal mines. A reasonable breaking span is greatly significant to ensure safe and efficient exploitation of coal mines. The hard roof of the short-wall working face is difficult to break during the mining process. Hence, the II646 fully mechanized coalface of the Zhuzhuang Coal Mine in a mining area in Huaibei, China was taken as the engineering background. Based on the theory of elasticity mechanics, an elastic thin-plate mechanical model of short-wall working faces was established, with the condition of two opposite edges simply supported and with one edge clamped and the other edge free (SCSF). The fracture law of hard roof was studied via theoretical analysis and onsite monitoring. Results show that the breaking span of the hard roof of the II646 working face is 80–90 m. The calculation results of the thin plate mechanical model are closer to the actual situation on-site than the calculation results of the traditional cantilever beam model. By performing calculations with maximum tensile stress theory and a bearing load capacity, the reasonable breaking span was 35 m. Based on the results of the theoretical analysis, the roof weakening scheme of the long-hole pre-splitting blasting was proposed for the II646 working face. The field practice results show that, after using deep-hole pre-splitting blasting, the periodic weighting interval and the working resistance of the support are approximately 35 m and less than 40.1 MPa, respectively. Both of these numbers indicate a decrease compared with before the roof weakens, which the periodic weighting interval (90 m) and working resistance of support (greater than 40.1 MPa), thus avoiding support collapse accidents and achieving safe and efficient mining of the short-wall working face. Such results can provide a scientific basis for the hard roof treatment of short-wall, fully mechanized working faces under similar conditions.

Keywords: Short-wall working face, Hard roof, Theory of elastic thin plate, Periodic fracture, Long-hole pre-splitting blasting

1. Introduction

Thin coal seams that are less than 1.6 m thick are widely distributed in China. Thin coal seams in the southwestern, northeastern, and eastern regions comprise a considerable percentage of China's coal reserves. The exploitation of thin coal seams plays a key role in successive exploitation in mining areas or the exploitation of liberated seams, thus improving the resource recovery rate and alleviating the regional contradiction between supply and demand of coal. In recent years, geological conditions start to deteriorate with the increase in coal demand and exploitation intensity. Irregular stopes are further exploited under the influence of geological structures, folds and faults, attitudes of rocks, and mining conditions. The "knife-handle style" working faces exist in many mining areas in China, such as those in Huainan, Huaibei, Datong, and Shendong, thus changing the length of working faces in the stope (lengthened or shortened). In such working faces, the typical short-wall mining applies to the knife-handle part, which is generally short. The overburden migration law and the characteristics of ground pressure behavior of these working faces attract extensive attention from scholars in the fields of coal-mine engineering and rock mechanics. Previous research on the law of overburden migration and ground pressure behavior in long-wall exploitation mainly focused on the structural instability and the movement of the overlying strata. Hypotheses on the inherent characteristics of strata behavior, such as the voussoir beam hypothesis [1], transferring rock beam theory [2], and key strata theory [3], were proposed. In mining thin coal seam short-wall, especially the state of the hard roof above the coal seam, the stress state of the roof differs from that in long-wall mining, indicating a typical stress state of the clamped and simple supported. This stress state directly affects the characteristics of roof fracture and ground pressure behavior. Research on the periodic fracture model and the pressure control of the hard roof of the thin coal seam short-wall face has practical significance. Based on the above analysis, the current study examines the mechanical characteristics of the hard roof of the thin coal seam short-wall face and established its fracture model. The findings can provide an experimental basis for the further study of rock migration law and ground pressure control of the thin coal seam short-wall face.

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2. State of the art

To ensure the safe mining of the working face, many researchers focused on the caving law of hard roofs and carried out similar simulation experiments and field measurements on the structural characteristics of overlying strata. The trapezoidal [4, 5] and the O-ring models [6, 7], which depict the shape of the overlying strata after a fracture is generated in the layered rock mass, were proposed. Besides, the overburden migration law and the stress distribution of the working face were analyzed via theoretical analysis and experimental research [8-10]. In general, existing research paid more attention to the characteristics of roof fracture and caving rather than the influence of the length of the working face. However, in onsite monitoring, the change in length of the working face greatly affects the fracture of the roof. The hanging area of the roof increases with the length of the working face. The roof then tends to rupture. By contrast, the hanging area of the roof decreases with the length of the working face, and the roof is not likely to rupture [11]. Therefore, the actual fracture shape of the overlying strata must be considered in the study of the roof fracture and the pressure characteristics of a short-wall face. However, previous studies simplified the roof to a beam structure and researched the influence of the characteristics of ground pressure. Research on ground pressure shows that the following changes occur as the length of working face increases: the weighting length decreases; the support load increases during the no pressure change period; the ground pressure intensity increases; and the impulsive load of the roof becomes much greater than the maximum resistance of the support. As the length of the working face decreases, a similar change tendency is also observed [12]. The change in working face length also greatly influence ground pressure. Previous research on the method of simplifying the roof to a beam model and using it to study ground pressure ignored the influence of working face length, and explaining the characteristics of the roof collapse behavior is difficult. With actual engineering as the background, the study analyzed the periodic fracture model and the control of the hard roof of the thin coal seam short-wall faces by using a plate model, which accords with the actual forced state. Such an analysis will contribute to the further understanding of the deformation, rupture, and collapse mechanism of the roof strata in short-wall exploitation.

In the research on hard roof control, Guo et al. [13] and Zuo et al. [14] combined fracture theory with rock blasting and proposed long-hole cumulative blasting to weaken the hard roof. Kuili et al. [15] adopted the 3D discrete element method to numerically calculate the influence of blasting on rock mass strength during blasting excavation in a deep roadway. Their study cast a new light on the numerical simulation of the dynamic blasting process via the discrete element method. Konicek et al. [16] proposed to release the strain energy of a floor and its surrounding rock mass via blasting. By using this method, the hard roof can be weakened to avoid rockburst during long-wall exploitation and reduce the support pressure of the working face. Previous research focused on the effect of blasting on the roof, and they often determined the presplitting step during blasting by performing the engineering analogy method. Relevant research is further required to determine a reasonable pre-splitting blasting step. In this manner, the hard roof can be substantially weakened, and engineering economic benefits can be improved. Therefore, in this study, the internal relationships of the fracture law of hard roof, the characteristics of ground pressure behavior in the working face, and the change law of support load are comprehensively analyzed. Moreover, based on support strength, the criterion to judge support instability caused by roof fracture is established to determine the reasonable blasting step.

Hence, given the shortcomings of existing research, the mining of a short-wall working face in the thin coal seam of Zhuzhuang Coal Mine in a mining area in Huaibei, China is taken as the research background in this study. The hard roof rock stratum mechanical model and the fracture model, which are highly similar to the actual project, are proposed to investigate the mechanical characteristics of hard roof. Furthermore, following the actual situation of the project, the roof control scheme of long-hole pre-splitting blasting is developed. By comparing the theoretical and the practical results in actual engineering, the rationality of the periodic roof fracture model of the short wall working surface proposed is discussed. This study can provide a reference for the research on the caving law of hard roof in thin coal seam short-wall working faces and the inspection of the application effect of the hard roof control scheme.

The remainder of this study is organized as follows. Section 3 establishes the fracture model of the hard roof and proposes the method for calculating the safe periodic weighting interval of the roof. Section 4 discusses the experimental results of the initial and periodic fracture of the hard roof rock layer and the reasonable determination method of the pre-splitting blasting cycle step through case studies. Section 5 summarizes the conclusions.

3. Methodology

3.1 Periodic fracture mechanics model of the roof

The roof of the II646 working face of the Zhuzhuang Coal Mine is composed of medium- and fine-grained sandstone with a compressive strength of 70 MPa, tensile strength of 3.4 MPa, Poisson's ratio of 0.21, elastic modulus of 30 GPa, and thickness of 18 m. The lithology of the roof is hard and integral and thus can be approximated as a continuous medium for the analysis of its stress state. The average thickness and buried depth of the mining coal seam are 1.6 m and 310 m, respectively. The length of the working face is 110 m. After the coal seam (specifically the thin coal seam) is mined, the hard roof is suspended and can be regarded a thin-plate mechanical model supported by a surrounding coal wall. Before the first weighting, the roof is supported by the coal wall of the working face and setup entry, and the other two opposite coal walls of the goaf. The periphery of the roof hardly moves and cannot realize free rotation. Hence, it can be idealized as under fixed constraint. The initial support condition of the hard roof is completely clamped and supported. After the first weighting, the side roof of the goaf becomes ruptured and then collapses. Relevant studies assumed that the roof is clamped and supported on the coal wall of the working face [17]. However, for the hard roof of the thin coal seam short-wall face, the roof of the coal walls of the goaf undergoes rotational displacement due to the fracture caused by the first weighting, and the roof support condition can be assumed to be two opposite edges that are simply supported. The anterior roof of working face remains to be under fixed constraint, and its roof support condition can be assumed to be one with its edge clamped. Therefore, the support condition of the hard roof can be described as two opposite edges that are simply supported, with one edge clamped and the other edge-free (SCSF), as shown in Fig. 1. The lengths of the thin plate at the x, y, and z directions are assumed to be the lengths of working face a, the advance distance of working face b, and the thickness of hard roof h, respectively. The top roof is subjected to a vertical triangular load q. Eq. (1) can be obtained as follows:

$$q = q_r(1 - y/b) \quad (1)$$

where q_r is the gravity stress of the upper overlying strata.

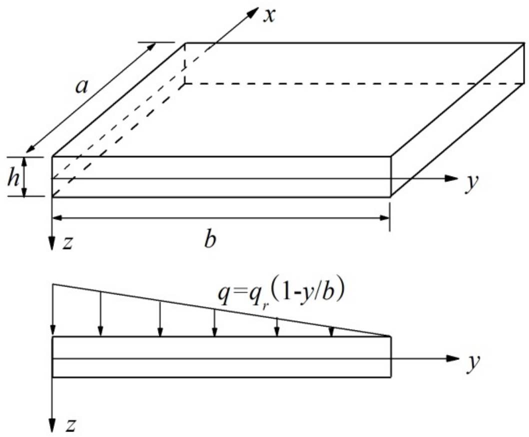


Fig. 1. Rectangular thin plate under in-situ stresses

3.2. Thin plate deflection and stress function of the periodic fracture of the hard roof

According to elasticity theory, the deflectional differential equation of the SCSF rectangular thin plate is

$$D\nabla^4 w(x,y) = q(x,y) \quad (2)$$

where D is the flexural rigidity of the thin plate, $D = Eh$.

The thin plate boundaries at $x = 0$, $x = a$, and $y = 0$ are clamped and supported, and $y = b$ is free. The boundary condition is given by

$$w\big|_{x=0,a} = 0, \left.\frac{\partial w}{\partial x}\right|_{x=0,a} = 0, w\big|_{y=0} = 0, \left.\frac{\partial w}{\partial y}\right|_{y=0} = 0 \quad (3)$$

The theoretical analysis of thin plate deflection in this study is based on the Ritz method. It also satisfies the boundary condition of the thin plate and the principle of the minimum potential energy of its equilibrium differential equation [18]. According to the calculation of the small deflection bending problem of the thin plate, the deflection w is assumed to be the only unknown function, and the remaining components are represented by w. The formula of the deflection w of the SCSF rectangular plate under hydrostatic pressure is

$$w = \sum_{m=1,3,5,\cdots}^{\infty} C_m w_m = \sum_{m=1,3,5,\cdots}^{\infty} C_m \sin\lambda_m x\left(\frac{y}{b}\right)^2 \quad (4)$$

where C_m is the mth independent undetermined coefficient, and w_m is a function defined to satisfy the boundary condition. The formula of λ_m is $m\pi/a$.

The deflection function satisfies the boundary condition of Eq. (3), where C_m is an undetermined constant. The strain energy V of the constant-thickness plate can be expressed as follows:

$$V_\varepsilon = \frac{D}{2}\iint_A \left\{ \begin{aligned} &\left(\frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2}\right)^2 - 2(1-\mu) \\ &\times\left[\frac{\partial^2 w}{\partial x^2}\frac{\partial^2 w}{\partial y^2} - \left(\frac{\partial^2 w}{\partial xy}\right)^2\right] \end{aligned} \right\} \mathrm{d}x\mathrm{d}y \quad (5)$$

where A is the area of the rectangular thin plate.

Substituting the second-order derivative of the deflection function w with respect to x and y into Eq. (5), the strain energy V can then be obtained as follows:

$$V_\varepsilon = \sum_{m=1,3,5,\cdots}^{\infty} \frac{DC_m{}^2}{2}\left[2 + \left(\frac{4}{3} - 2\mu\right)\lambda_m^2 b^2 + \frac{1}{10}\lambda_m^4 b^4\right]\frac{a}{b^3} \quad (6)$$

The first derivative of the strain energy V with respect to C_m in Eq. (6) is

$$\frac{\partial V_\varepsilon}{\partial C_m} = DC_m\left[2 + \left(\frac{4}{3} - 2\mu\right)\lambda_m^2 b^2 + \frac{1}{10}\lambda_m^4 b^4\right]\frac{a}{b^3} \quad (7)$$

According to Eq. (4),

$$\begin{aligned} \iint_A q_r w_m \mathrm{d}x\mathrm{d}y &= \iint_A q_r\left(1 - \frac{y}{b}\right) w_m \mathrm{d}x\mathrm{d}y \\ &= \int_0^a\int_0^b q_r\left(1 - \frac{y}{b}\right)\left(\frac{y}{b}\right)^2 \sin\lambda_m x \mathrm{d}x\mathrm{d}y = \frac{q_r b}{6\lambda_m} \end{aligned} \quad (8)$$

According to the principle of minimum potential energy [19],

$$\frac{\partial V_\varepsilon}{\partial C_m} = \int_0^a\int_0^b q_r w_m \mathrm{d}x\mathrm{d}y \quad (9)$$

Substituting Eqs. (7) and (8) into Eq. (9), the coefficient C_m can then be obtained.

$$C_m = \frac{q_r b^4}{6m\pi D\left[2 + \left(\frac{4}{3} - 2\mu\right)\lambda_m^2 b^2 + \frac{1}{10}\lambda_m^4 b^4\right]} \quad (10)$$

Then, substituting Eq. (10) into Eq. (4), the deflection function w can be obtained.

$$w = \sum_{m=1,3,5,\cdots}^{\infty} \frac{q_r b^2 \sin^2\lambda_m x \cdot y^2}{6m\pi D\left[2 + \left(\frac{4}{3} - 2\mu\right)\lambda_m^2 b^2 + \frac{1}{10}\lambda_m^4 b^4\right]} \quad (11)$$

Substituting w of Eq. (11) into the stress and deflection functions of the elastic thin plate, the formula of the stresses σ_x and σ_y and the shear stress τ_{xy} of the SCSF thin plate can be obtained.

$$\begin{cases} \sigma_x = \sum\limits_{m=1,3,5,\cdots}^{\infty} -12C_m D \dfrac{2\mu - \lambda_m^2 y^2}{b^2 h^3} \sin \lambda_m x \cdot z \\ \sigma_y = \sum\limits_{m=1,3,5,\cdots}^{\infty} -12C_m D \dfrac{2 - \mu\lambda_m^2 y^2}{b^2 h^3} \sin \lambda_m x \cdot z \\ \tau_{xy} = \tau_{yx} = \sum\limits_{m=1,3,5,\cdots}^{\infty} -24C_m D\lambda_m \dfrac{(1-\mu)}{b^2 h^3} \cos \lambda_m x \cdot yz \end{cases} \quad (12)$$

3.3. Roof fracture criterion and working face stress state

The tensile strength of a rock is much smaller than its compressive strength. Hence, maximum tensile stress theory is used as the criterion for the roof fracture [20].

$$\sigma_{\max} < \sigma_t \quad (13)$$

where $\sigma_{\max}$ is the maximum tensile stress of the roof, and σ_t is its tensile strength.

When roof fractures and periodic weighting occur, the fractured rock mass can be assumed to have a cantilever rock beam. The hydraulic support is in equilibrium under the combined effects of roof overburden load q, additional force Q generated by the clamping action at the fractured part of the roof, and load resultant force of hydraulic support P. The stress state is shown in Fig. 2.

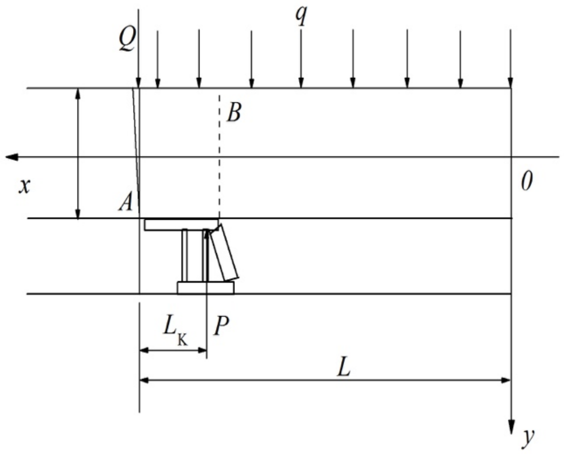


Fig. 2. Instability during periodic weighting

According to elastic mechanics, the roof stress σ_x in the cantilever state can be obtained.

$$\sigma_x = -\frac{6q}{h^3} x^2 y + \frac{4q}{h^3} - \frac{3q}{5h} y \quad (14)$$

When the cantilever rock beam is broken, as a means of maintaining the stability of the roof, the $\sigma_{\max}$ of point B above the tangent line should reach the ultimate tensile strength σ_t to ensure that the suspended ceiling of the goaf completely collapses.

$$\sigma_t = \frac{3q(L - L_k)^2}{h^2} - \frac{q}{5} \quad (15)$$

where L is the breaking span of the roof, and L_k is the hydraulic support roof spacing.

The equilibrium conditions at the roof-breaking moment are

$$\begin{cases} \sum F_\perp = 0 \quad P = qL_k + q(L - L_k) + Q \\ \sum M_0^{'} = 0 \quad QL_k + \dfrac{1}{2} qL_k^2 = \dfrac{1}{2} q(L - L_k)^2 \end{cases} \quad (16)$$

According to Eqs. (15) and (16), the load acting on the working face support when the roof fractures is given by

$$P = \frac{1}{2} qL_k + \frac{h^2 L_k \left(\sigma_t + \dfrac{q}{5}\right) + 3q(L - L_k)^3}{6L_k^2 (L - L_k)} \quad (17)$$

During the mining of the working face, as a means of ensuring the safety of the hydraulic support, the load P on the working face support should not be greater than the yield load P_s of the support when the roof fractures. Therefore, the safe periodic weighting length of the roof L_s can be obtained by Eq. (17).

$$L_s \le \frac{6(2P_s - qL_k)L_k^3 + 2\left(\sigma_t + \dfrac{q}{5}\right)h^2 L_k}{6(2P_s - qL_k)L_k^2 - 2\left(\sigma_t + \dfrac{q}{5}\right)h^2} \quad (18)$$

4. Result, analysis, and discussion

4.1. Roof deformation and mechanical characteristics

According to the mechanical parameters of the roof rock mass and the size of the II646 working face in Zhuzhuang Coal Mine, the working face is assumed to advance by 90 m. According to Eqs. (10)–(12) and the first major item of the series, m = 1 (the larger m is, the more accurate the result will be). Figs. 3 and 4 show the distributions of flexural deformation w and stresses σ_x, σ_y, and shear stress τ_{xy} on the roof ($z = -h/2$) under the gravity stress of the rock mass.

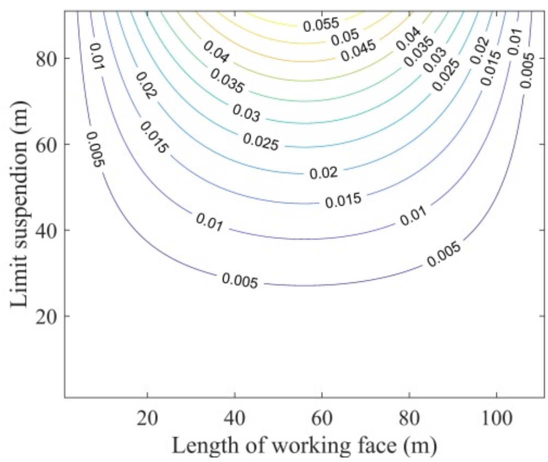
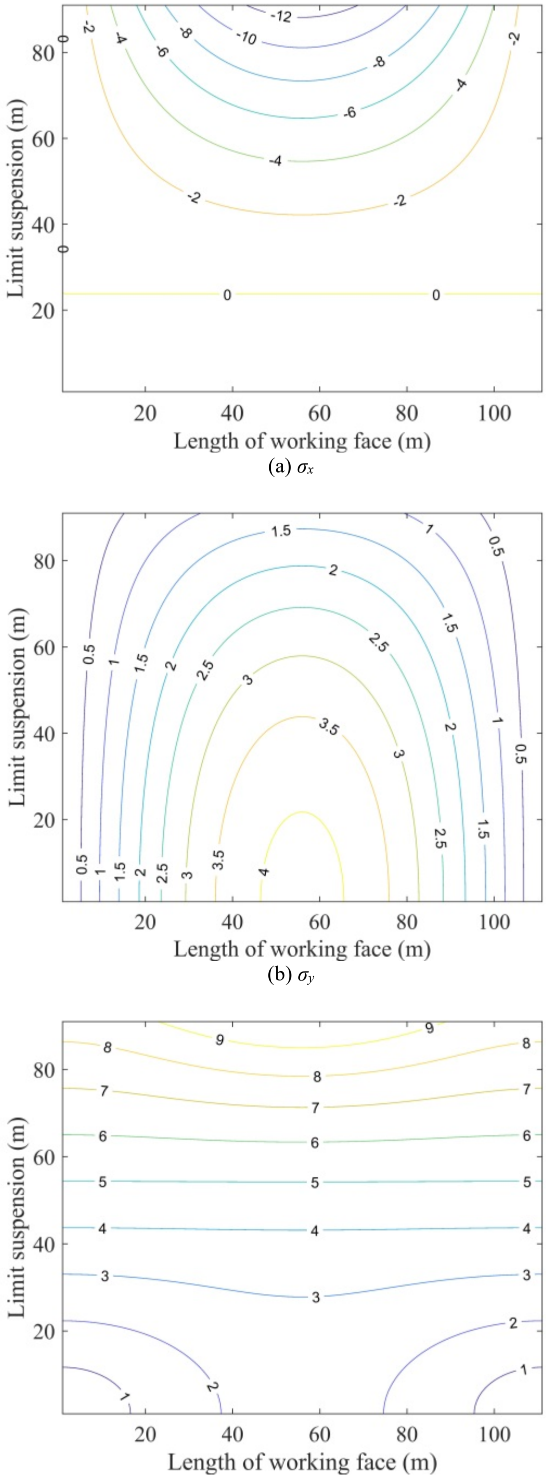


Fig. 3. Deflection of the roof

As shown in Figs. 3 and 4, under the self-weight load pressure of the upper overlying strata, the deflection of the roof in the SCSF state gradually increases from the working face part to the part end of the goaf, and the left–right symmetrical distribution with the centerline of the goaf, and changes along with the working face increase and then decrease. The maximum value of the deflection (55 mm) appears at the center of the end of the goaf. On the upper part of the hard roof, compressive stress occurs along the working face, and the maximum value of −12.35 MPa appears at the center of the end of the goaf above the roof. The tensile stress occurs along the direction of mining, and the maximum value of 4.152 MPa appears at the center of the working face above the roof. The maximum shear stress value of 9.307 MPa also appears at the center of the end of the goaf above the roof, whereas the minimum shear stress value of 68.68 kPa appears at the left and right ends of the working face.



(a) σ_x

(b) σ_y

(c) τ_{xy}

Fig. 4. Stress distributions of the roof

The tensile strength of the hard roof of the II646 working face of Zhuzhuang Coal Mine is approximately 3.4 MPa. As shown in Fig. 4(b), when the working face advances by 90 m, the tensile stress on the roof, which is 30–80 m away from the left end of the working face, is greater than its tensile strength. This scenario will cause tensile failure. The failure range accounts for about half the length of the working face. In this case, the roof undergoes overall instability. Assuming that the advance distance of the working face differs, the relationship between the exposed width of the roof and the maximum tensile stress of the SCSF model can be obtained, and the results calculated by the traditional cantilever beam model can be compared. As shown in Fig. 5, the results calculated by the two models are prominently different. With the increase in the exposed width of the roof, the stress obtained by the cantilever beam model grows fast. By taking the tensile strength of the roof of 3.4 MPa as an example, the SCSF model indicates that tensile failure will occur when the exposed width of the roof is 70 m. However, according to the cantilever beam model, the roof will lose its stability when the exposed width of the roof is 34 m. Large-scale fractures and a support collapse accident occurred when the working face advanced by 80−90 m according to an onsite monitoring report on the roof of the II646 working face of the Zhuzhuang Coal Mine. Thus, the proposed SCSF model can achieve highly accurate calculation results under short-wall mining conditions.

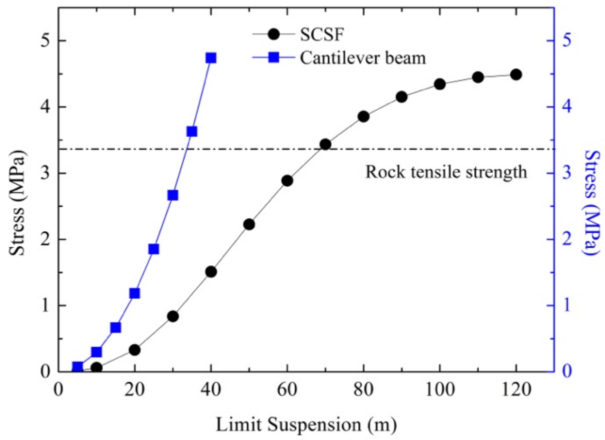


Fig. 5. Tensile stress of roof under different limit suspensions

4.2. Reasonable periodic breaking span and control technology

In the course of fractured subsidence, the roof can be assumed as a cantilever beam. The influence of cantilever beams of different lengths on the working resistance of the working face hydraulic support can be obtained by Eq. (17), as shown in Fig. 6. According to the figure, with the increase in the length of the cantilever beam, the resistance of the hydraulic support surges in the quadratic curve rapid growth trend. According to the SCSF model, the roof starts to fracture when it is 70 m away from the working face. At this time, the resistance of the hydraulic support is 156 MPa, which far exceeds the yield load (40.1 MPa) of the ZY5000-09/20 hydraulic support. In this case, the normal operation of the equipment interferes. Thus, the roof pressure may far exceed the support capacity of the hydraulic support when the hard roof fractures, resulting in support collapse accidents during the mining of the short-wall working face of the thin coal seam. According to the monitoring report on the hydraulic support during the mining of the working face, support collapse accidents occurred on 7 June 2010 and 18 August 2010, respectively, in which the working face mining by 90 m. The immobile hydraulic supports due to the support collapse accidents are shown as red boxes in Fig. 7. The reasonable breaking span should be determined by the yield load of the hydraulic support to ensure the normal operation of the hydraulic support. According to Fig. 6, the reasonable breaking span of the II646 working face should be less than or equal to 35 m. Therefore, after the support collapse accident on 18 August 2010, pre-splitting blasting is applied to weaken the hard roof at intervals of every 35 m in front of the working face. The weakened part is shown as dashed lines in Fig. 7.

Long-hole pre-splitting blasting is a commonly used method to weaken the roof before exploitation [21, 22]. Based on the conditions of the II646 working face, the corresponding method of roof pre-splitting blasting is proposed to avoid the support collapse accident. The blast-hole distributions are shown in Fig. 8, from the tail entry and head entry to the roof drilling 6 and 2 blast-holes, respectively. All blast-holes are charged cartridge of the coal mine permitted water-gel explosives. Each cartridge has a diameter of 60 mm, a length of 1 m, and a weight of 3.4 kg, and packed in antistatic plastic tubes. Each cartridge contains a 1-meter-long coal mine permitted detonating fuse to ensure stable detonation. Based on the conditions of the II646 working face, the charge lengths in the different blast-holes ranges from 20 to 65 m. The charge coefficient between 66% and 82% and each blast-hole charged with 68−221 kg of explosive. The total charge of the blast-hole is 847 kg. Parameters adopted for pre-splitting blasting in the II646 working face, as shown in Table 1. The blast-hole detonation adopts millisecond blasting to ensure the good presplitting effect. No. 2, 4, 6, and 8 blast-holes are adopted coal mine permissible one-segment MS delay electric detonators, whereas No. 1, 3, 5, and 7 blast-holes are adopted coal mine permissible three-segment MS delay electric detonators.

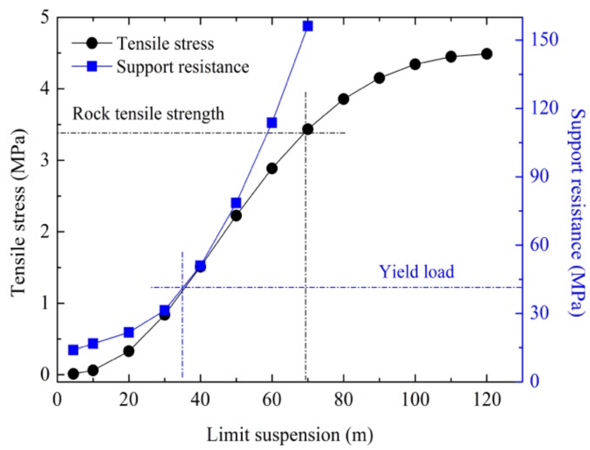


Fig. 6. Working resistance of support under different limit suspensions

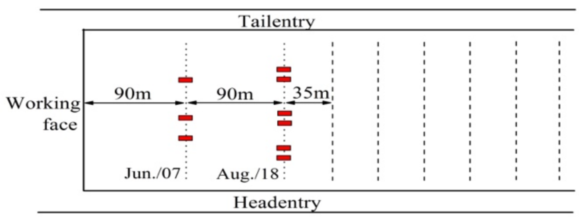


Fig. 7. Statistical results of support collapse accident

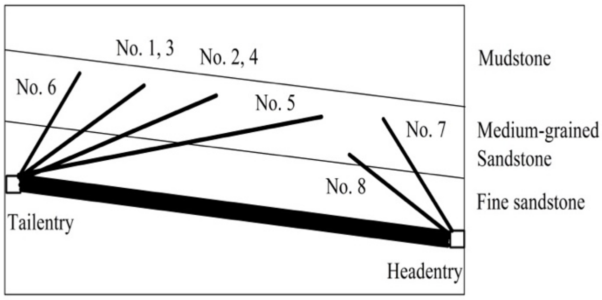


Fig. 8. Blast-hole distributions from the long-hole pre-splitting blasting design in the II646 working face

4.3. Onsite roof control effect

Fig. 9 shows the working resistance of the hydraulic support during the mining of the II646 working face. Before the support collapse accident, the working resistance of hydraulic support in the working face is in the yield-load state for a long time, as shown by the arrows a and b in Fig. 9. After the long-hole pre-splitting blasting has performed on the hard roof in front of the working face, the working resistance of the hydraulic support increases slowly with the advancement of the working face. The hydraulic support reaches the value of the yield load over at a short time only when the fracture occurs, and it decreases rapidly after the fracture, as shown by the arrows c, d, e, f, g, and h in Fig. 9. Thus, the weakening of the hard roof can help reduce the load on the working face, and the periodic weighting interval of the roof subsequently falls significantly. The hydraulic support can fully adapt to the periodic fracture of the roof, and a support collapse accident is successfully avoided.

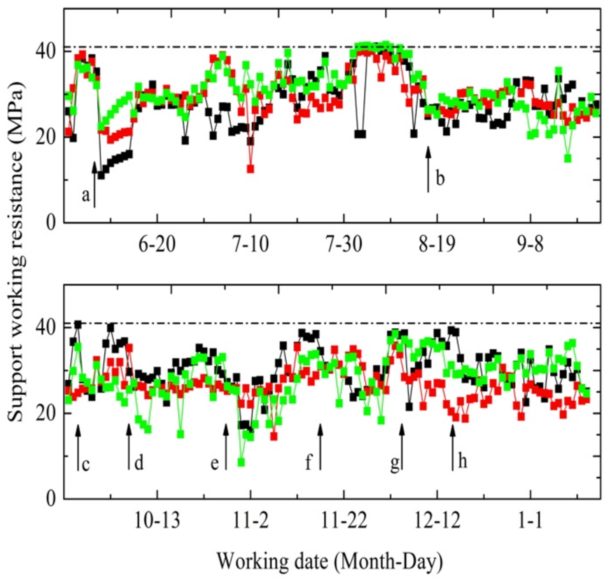


Fig. 9. Curve of support working resistance

5. Conclusions

The SCSF model is proposed to study the fracture characteristics and the control method for a hard roof in a thin coal seam short-wall working face. The mechanical model of the periodic weighting of the working face is established based on the fracture criterion of rock. The deformation and stress distribution rules of the short-wall working face and the changes in the working resistance of the hydraulic support are analyzed, which combined the onsite monitoring date of the working resistance of the hydraulic support with the result of theoretical analysis. The following conclusions can be drawn:

Table. 1. Parameters adopted for long-hole pre-splitting blasting in the II646 working face

Number of borehole	Angle of elevation (°)	Length (m)	Diameter (mm)	Percentage of loaded length of boreholes (%)	Explosive charge (kg)
1	24	32	75	68.75	75
2	12	50	75	80.00	136
3	24	32	75	68.75	75
4	12	50	75	80.00	136
5	5	80	75	81.25	221
6	30	30	75	66.67	68
7	39	30	60	66.67	68
8	26	30	60	66.67	68

(1) Simplifying the roof of the short-wall working face into a thin plate mechanical model conforms better with the actual situation of the project in comparison with the use of the traditional cantilever beam model. According to its mechanical state, the hard roof is assumed to be an SCSF thin plate. The single-triangle series is used to simulate the self-weight of the rock and obtain the flexural deformation function of the roof. The formulas of internal force and stress function of the rectangular thin plate are obtained according to the principle of minimum potential energy and small deflection bending theory of thin plates. After the calculation, the roof caving interval of the II646 working face roof is 80–90 m, and the overall instability fracture occurred on the roof.

(2) The formula of the working resistance of the hydraulic support at the fracture of the roof is obtained based on the maximum tensile stress theory. The reasonable breaking span is determined to be less than 35 m by combining the formula with the onsite monitoring results. A scheme to weaken the hard roof of the short-wall working face is proposed to ensure the normal operation of the hydraulic support.

(3) The method of weakening the hard roof by the long-hole pre-splitting blasting of the working face reduces the periodic weighting interval of the roof. This scheme not only effectively prevents the large area of the working face from being suspended and catastrophic caving from occurring, but it also ensures the normal operation of the hydraulic support and the safe mining of the II646 fully mechanized face. Besides, the method provides a scientific basis for the treatment of the hard roof of the short-wall fully mechanized face.

The short-wall face roof is assumed to be an SCSF stress model in this study. The boundary conditions may require further optimization under the influence of adjacent working face in the engineering field. Therefore, further studies are necessary to determine the influence of boundary conditions much closer to the onsite situation on the stress distribution and fracture of the roof. Such future studies will help comprehensively explain the mechanical characteristics of the hard roof of the short-wall working face.

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