



Analysis on the Breaking Law of Soft and Thick Roof of Fully Mechanized Top-Coal Caving Face

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Abstract The study of roof breaking law is very important for the behavior of the underground pressure in fully mechanized top-coal caving face under the condition of weak roof. In this paper, the research is to study the soft and thick roof breaking law in the fully mechanized top-coal caving face 2–100 in coal seam 2#. The theoretical analysis, numerical simulation and field measurement methods are used to analyze the breaking law of the weak thick layer roof in the fully mechanized top-coal caving face. First, the mining conditions of the working face are introduced systematically, the mechanical properties of the weak roof are analyzed, the mechanical model of the immediate roof caving structure and the mechanical model of the main roof fracture structure are established, and the instability characteristics of the immediate roof and the main roof are analyzed. Through UDEC numerical simulation, the failure structure of the soft and thick roof in fully mechanized caving face, the plastic zone and stress distribution of the roof under different propulsive lengths, and the roof subsidence of the basic roof are obtained. It is found that the immediate

roof caving will form an “arch” structure, and the main roof fracture will form a “three hinge arches” structure. Under this mine condition, the initial roof caving step is 17.8 m, and the main roof initial fracture step is 41.3 m, the periodic fracture step distance is 16.7 m. Under the condition of instability of immediate roof “arch” structure, when the displacement distance of the vault reaches 5.1 m, the “arch” structure will be unstable. Conditions of sliding instability of main roof “three hinge arches” structure: the ratio of coal seam thickness to the span of main roof is less than 0.2, and when the back angle is less than 8°, it is not easy to slip and lose stability. Through the observation of the field measurement results of fully mechanized top-coal caving face 2–100, the breaking rule of the soft and thick roof in fully mechanized top-coal caving face is verified.

Keywords Fully mechanized top-coal caving face · Soft and thick roof · Numerical simulation · Breaking law

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1 Introduction

Fully mechanized top-coal caving mining technology is the development direction of mining technology in thick coal seam mining area (Wang 2005, 2013; Cheng et al. 2019a; Wu 1999). The low recovery rate

of top coal is a big problem in top coal caving mining. In addition, roof breaking law is also a key problem to be solved in fully mechanized top coal caving (Kong et al. 2019; Yang et al. 2019). A lot of research work has been done on this issue by scholars.

Some scholars have studied the breaking law of hard roof under fully mechanized top-coal caving face. In view of problem of the strong ground pressure behavior in the working face casing by the key stratum fracture and instability of the thick and hard immediate roof and key stratum in the extra thick coal seam, the deep hole blasting technology is used to pre crack the thick and hard immediate roof and key stratum in front of working face to weaken the strength of the hard rock layer. The blasting effect of roof is verified by the comprehensive observation of drilling, micro-seismic monitoring and working resistance of support, which ensures the safe production of working face (Li 2019). According to the stability characteristics of roof movement in fully mechanized top-coal caving face, the movement law and “key” problems of thick layer hard roof in fully mechanized caving face in the initial weighting are solved, and the influence of the change of top coal caving rate in the initial weighting and normal advance stage on the structural stability of thick layer hard roof is expounded (Shi 2005). Based on the discussion of the breaking law of multi-layer roof and the determination of the support resistance of the extra thick coal seam in fully mechanized top-coal caving face, the principle and method of the determination of the support working resistance are obtained (Liu et al. 2015). The characteristics of roof fracture and the law of overburden movement in fully mechanized top-coal caving face with hard roof are analyzed (Zheng and Kong 2019). The problem of large deformation and even roof falling disaster control in the process of roof support in soft thick seam of super large cross-section roadway has been studied (Yan et al. 2014). Under the condition of “two hard” condition, the stress in the coal seam with isolated island type short pillar face is highly concentrated, the roof boundary condition is complex, and the influence of multiple mining is easy to cause the dynamic failure of roof disturbed surrounding rock. In order to improve the control effect of surrounding rock in this kind of stope, the fracture form of hard roof, the form of surface pressure and the cause of dynamic damage of surrounding rock were analyzed by means of field measurement and theoretical analysis (Yang

et al. 2016). Based on the failure control condition of “strength parameter - stress environment - joint weak surface” of coal and rock mass, the deformation and fracture characteristics of overburden in large and high stope are studied, and the movement evolution process of overburden caused by mining is reappeared through laboratory tests. Finally, the method of determining the working resistance of support is theoretically analyzed according to the roof structure (Wang and Cheng 2016). Understanding the behavior of the top-coal caving mining face and immediate roof can be used to enhance buffering effects. The mechanical properties of the coal-rock combined body (CRCB) play a vital role in the performance of overburden load transmittance and support resistance design. They define and derive the relative physical and mechanical parameters of CRCB to illustrate and analyze the influence of coal-rock height ratio (CRHR), coal and rock mass behavior, and interface parameters on CRCB mechanical properties. Sensitive analysis shows that the rank of influential factors on CRCB properties is $CRHR/ECRHR > \text{coal strength} > \text{rock strength} > IA$ (Cheng et al. 2018, 2020). Other scholars have studied weak roofs, the construction safety and surrounding rock stability control measures of soft inter-layer roof roadway are put forward (Li 2008). There are soft rock layers in Yushujing coal mine, especially the roof-floor lithology of 11501 working face shows the characteristics as soft rock, resulting in the drift floor-heave and failure of bolt in the process of coal extraction, which affects safe and efficient mining. The results show that the surrounding rock mainly consists of kaolinite, illite, smectite and chlorite. Among these minerals, the smectite’s great hygroscopicity and high expansibility take the main factor for the deformation of surrounding rocks. Therefore, it is suggested that reinforcing the surrounding rock and reducing the deterioration of water might be effective ways to keep the stability of surrounding rock in soft rock roadway (Liu et al. 2020). The direct roof of weak layer has three failure forms: flexural failure, overall caving and arch caving. In this regard, based on the beam theory and the block theory, a mechanical model of roof rock beam and block was constructed to reveal the change rule of the failure form of the direct roof in the weak layer, and to provide a theoretical reference for the direct roof control and support scheme design of the roadway in the weak layer (Chen et al. 2020).

In conclusion, many domestic scholars have studied the law of the ground pressure behavior during the mining of the fully mechanized top-coal caving face, especially for the ground pressure behavior under the condition of the hard roof, and have achieved fruitful research results, which has laid a solid theoretical foundation for the safety promotion of the working face. However, in the fully mechanized top-coal caving mining of the thick coal seam with weak roof, the breaking law of the roof and the characteristics of the mine pressure have not been studied in depth. Therefore, based on the fully mechanized top-coal working face 2–100 of coal seam 2#, this paper studies the failure and instability characteristics of the weak roof by theoretical analysis and numerical simulation, reasonably explains the law of the ground pressure behavior of the soft and thick roof, and verifies it by an engineering example.

2 Engineering Background

The fully mechanized top-coal caving face 2–100 of coal seam 2# of a mine is located in the first mining section. The thickness of the coal seam is 5.8 m, the dip angle is 0°–2°, the elevation of the working face is + 318 to + 330 m, the thickness of the bedrock is 370–459 m, the average depth is 420 m, the design length of the working face is 700 m, the mining length is 620 m, the length of working face is 200 m, and the design length of coal pillar is 40 m. (40 m from the

wind bridge of two roadway to working face 2–100). Roof and floor conditions: the main roof is fine-grained sandstone with an average thickness of 12 m, the immediate roof is mudstone with an average thickness of 7.8 m, the immediate floor is silt-stone with an average thickness of 5 m, and the main floor is fine-grained sandstone with an average thickness of 6 m (Fig. 1).

3 Fracture Characteristics of Weak Roof—Theoretical Analysis

According to the analysis of fully mechanized top-coal caving face 2–100, in the process of the soft roof breaking, the thickness of the immediate roof will affect the movement of the overburden strata, and then affect the change of the immediate roof as the load and the way of force transmission. Therefore, according to the thickness of the immediate roof, the soft rock layer as the main roof under the condition of fully mechanized mining, which has been part of the caving zone, cannot fill the goad, and will form the arch balance state. With the continuous advance of the working face, the caving overburden will eventually fill the goad and form a balance structure in the relatively weak overlying strata. The main roof is affected by the immediate roof breaking. With the increase of the advance distance, the main roof will break and form a voussoir beam structure (Fig. 2).

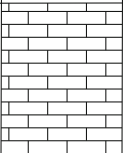

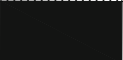


Name of roof	Name of rock	Average thickness/m	Columnar	Lithologic character
Mian roof	Fine-grained sandstone	12		Gray, fine-grained sandy structure with regular grain arrangement.
Immediate roof	Mudstone	7.8		Dark gray, muddy structure with plant fossil fragments.
Coal seam	2# coal	5.8		Black powder, good coal quality, contains plant fossils.
Immediate roof	Siltstone	5.0		Dark gray, silty structure, dense and brittle.
Mian roof	Fine-grained sandstone	6.0		Light gray, fine-grained sandy structure with muddy stripes.

Fig. 1 Comprehensive columnar diagram of fully mechanized top-coal caving face 2–100

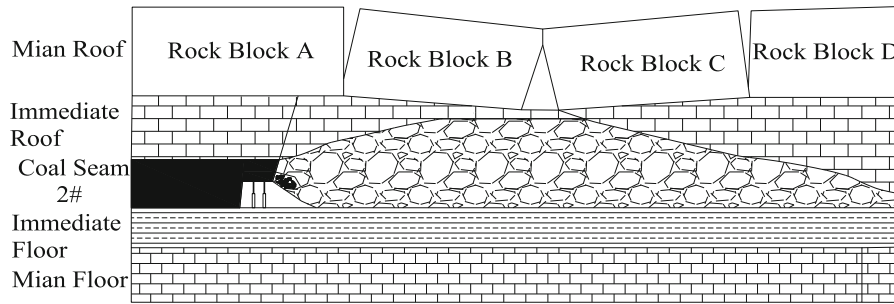


Fig. 2 Broken model of soft thick roof of fully mechanized top-coal caving face

3.1 Analysis of Immediate Roof Caving

According to the analysis, the change of the thickness and lithology of the immediate roof will result in the different equilibrium structure of the overburden movement and the different ground pressure behaviors of the working face. As the rock structure of fully mechanized top-coal caving face 2–100 is relatively simple, if the immediate roof fills the goad, the required thickness of the immediate roof is $\sum h$. As shown in formula (1):

$$\sum h = \frac{M}{K_p - 1} \tag{1}$$

In the formula: M is the thickness of coal seam, m ; the value of K_p is 1.25–1.50.

When the $M = 5.8$ m, the required thickness of immediate roof is about 11.6–23.2 m. Obviously, the thickness of the immediate roof will directly affect the movement of the overlying roof structure, and then affect the change of the main roof as the load and the way of force transmission. Therefore, according to the

thickness of immediate roof, due to the caving coal technology of caving mining, the immediate roof caving process has obvious gradual fluidity with the caving process, so it is easy to form an “arch” structure, which is the boundary between irregular caving zone and regular caving zone (Cheng et al. 2019b; Cai and Geng 2009; Liu and Cheng 2019; Zhang et al. 2019).

The mechanical geometric model of the “arch” structure of immediate roof was established, as shown in Fig. 3:

Assuming the combined stress σ on the plane AB and CD of the “arch” structure, σ is divided into shear stress τ_a and normal stress σ_a . when the “arch” structure reaches stress equilibrium, the equilibrium condition as shown in formula (2):

$$2\Delta h\tau_a = 2a\Delta h\rho g \tag{2}$$

In the formula: Δh is the unit height; $2a$ is the distance from top coal to compacted gangue; ρ is the density of rock mass.

In the analysis of the above-mentioned general expressions about the formation mechanism and shear force of the “arch” structure, in order to simplify the mathematical operation, the “arch” structure is assumed to be an ideal symmetrical arch structure. However, the actual “arch” structure is not asymmetric, and the height of the front arch foot and the rear arch foot is not equal.

Under the condition that the structure of the main roof strata is not unstable, the arch structure of the immediate roof continuously loses stability, recombines and moves forward with the advancement of mining (Li et al. 2008; Liu et al. 2018). In fact, with the advancement of mining, τ_a changes with time and space, so we need to further analyze the general expression formula of τ_a . If the initial shear stress

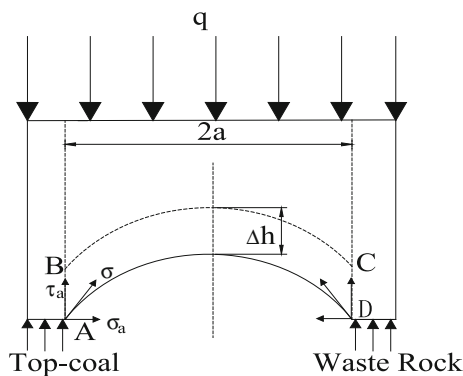


Fig. 3 Mechanical model of “arch” structure with immediate roof

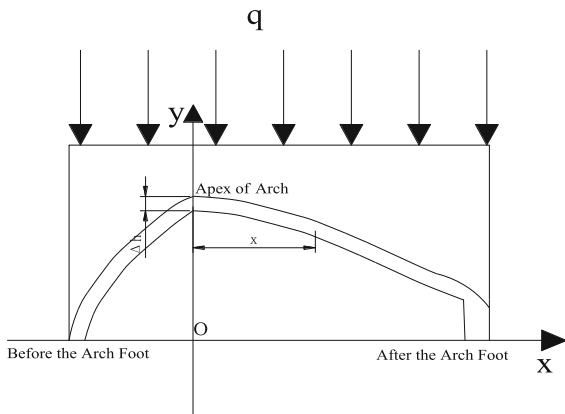


Fig. 4 Shear stress balance of actual “arch” structure

between the immediate roof is τ_0 , then $\tau_a = \tau_0 + \tan\varphi$ in formula (2), where φ is the internal friction angle. As shown in Fig. 4, x is the distance from a point on the arch to the center of the arch.

$$2x\Delta h\tau_a = 2x\Delta h\rho g \tag{3}$$

That is to say, $\tau_x = x\rho g = x\gamma$, in the formula (3): γ is the density of loose rock layer, $\gamma = \gamma'/k_p$, where γ' is the dense weight of original rock mass, and k_p is the coefficient of rock mass expansion.

It can be seen from formula (3) that the farther away from the center of the arch, the greater the shear force, but the bearing capacity of the “arch” structure is limited, which is subject to the shear strength of the immediate roof. Therefore, with the advancement of mining, the span of the “arch” structure continues to increase, and the front and rear arch feet of the arch will lose stability first. It can be concluded that when the shear strength of the immediate roof is less than the shear stress of the “arch” structure, the “arch” structure will lose its stability. Through calculation, when $x = 5.1$ m, the “arch” structure will lose stability.

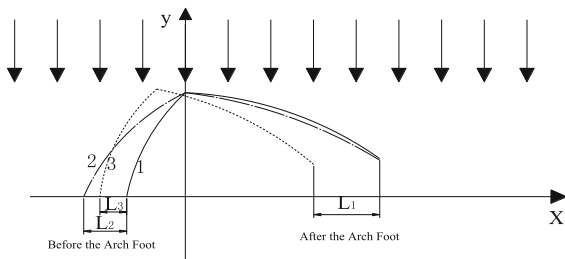


Fig. 5 Movement process of “arch” structure

Figure 5 shows two processes during the movement of the “arch” structure.

In the figure: L_1 is the movement distance of rear arch foot; L_2 is the instantaneous movement distance of front arch foot; L_3 is final movement distance of front arch foot.

First of all, the front arch foot moves forward to reach the maximum span of the arch immediately after the coal cutting and moving frame, as shown in 2 of Fig. 5. The distance between the back foot and the arch axis is larger than the front foot. Therefore, at this time, the gangue near the rear foot of the arch will lose its stability first, and will be compacted on the irregular caving zone as a part of the regular caving zone. Then, as the top coal in the elastic–plastic state continuously flows into the area to be released, the front arch foot will also lose stability and retreat, so that the whole “arch” structure of immediate roof will return to the original state, as shown in 3 of Fig. 5.

3.2 Fracture Analysis of Immediate Roof

When the fully mechanized top-coal caving face 2–100 is mined, the immediate roof breaks and fills the goad. With the continuous advance of the working face, the main top span increases gradually, and the fracture occurs when the limit span is reached. Therefore, before its fracture, the main roof of suspension can be regarded as a fixed rock beam model supported by coal rib at one end and boundary coal pillar at the other end (Miao and Qian 1995). As shown in Fig. 6.

The rock is easy to be damaged by tension or shear. The concrete failure mode is determined by internal stress state, tensile strength and shear strength. Therefore, it is of great significance to analyze the distribution of the maximum principal stress and the

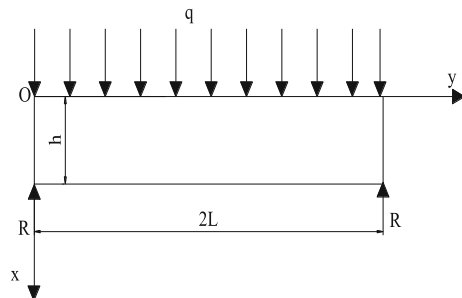


Fig. 6 Fixed rock beam model

maximum shear stress in the rock beam to study the fracture form, location and crack growth (Shi et al. 2014). The relationship between principal stress, maximum shear stress and stress component is as follows:

$$\begin{cases} \sigma_1 = \frac{\sigma_x + \sigma_y}{2} + \sqrt{\frac{(\sigma_x - \sigma_y)^2}{4} + \tau_{xy}^2} \\ \sigma_2 = \frac{\sigma_x + \sigma_y}{2} - \sqrt{\frac{(\sigma_x - \sigma_y)^2}{4} + \tau_{xy}^2} \\ \tau_{\max} = \sqrt{\frac{(\sigma_x - \sigma_y)^2}{4} + \tau_{xy}^2} \end{cases} \quad (4)$$

When the maximum principal stress σ_1 at the top of both ends of the immediate roof reaches its tensile strength σ_t , the ultimate span of the first fracture can be obtained (Wang et al. 2014).

$$L_C = 2h\sqrt{\frac{4\sigma_1 - (3\mu + 4)q}{8q}} \quad (5)$$

In the formula: q is the uniformly distributed load; μ is Poisson’s ratio; σ_t is the tensile strength.

Calculated: $L_C = 42.6$ m.

The initial pressure step distance of the main roof is as follows (Miao and Qian 1995).

$$L_c = h_1\sqrt{\frac{2R_T}{q}} \quad (6)$$

In the formula (6): h_1 is the basic top rock thickness; R_T is the basic tensile strength of the roof; q is the overlying load.

By calculation: $L_c = 41.3$ m.

The periodic weighting interval of the main roof is determined by the cantilever fracture.

$$L_z = h_1\sqrt{\frac{R_T}{3q}} \quad (7)$$

By calculation: $L_z = 16.7$ m.

3.2.1 Stress Analysis of Rock Mass with Mian Roof Fracture

It can be seen from the above primary fracture law of the main roof that in the process of advancing from the setup entry to the front of the working face, the tensile failure occurs at the top of both ends when the main roof reaches its limit span according to the fixed rock

beam structure. In the process of crack downward propagation, tensile failure occurs at the bottom of the middle part, and the crack propagates upward and finally breaks. Under the action of horizontal extrusion at both ends, the broken rock blocks are hinged to form a symmetrical three hinge arch structure (Wang and Cheng 2016; Zhao et al. 2019; Wang et al. 2019). As shown in Fig. 7.

For the three hinged arch structure, the resultant force in the vertical direction $\sum F_y = 0$, and the moment at point is $\sum MA = 0$, that can be obtained:

$$R_1 = R_2 = \frac{qL_{MN}}{2} \quad (8)$$

$$R_2L_{MN} = \frac{qL_{MN}^2}{2} \quad (9)$$

where L_{MN} is the horizontal distance between M and N joints, m; R_1 and R_2 are the shear forces at M and N joints, kN.

The stress analysis at point M of key block B shows that:

$$R_1L_{MK} = Ts + \frac{qL_{MK}^2}{2} \quad (10)$$

Substituting formula (8) into formula (10), we can get:

$$T = \frac{qL_{MK}^2}{2s} \quad (11)$$

It can be seen from Fig. 8 that if the overlying load of key block B is $Q = qL_{MK}$, the ratio of horizontal thrust to overlying load Q is λ .

$$\lambda = \frac{T}{Q} = \frac{L_{MK}}{2s} \quad (12)$$

According to the geometric relationship in Fig. 8, we can get:

$$\begin{cases} L_{MK} = h \sin \beta + \frac{L_C \cos \beta}{2} \\ s = h \cos \beta - \frac{L_f \sin \beta}{2} - a \\ a = \frac{2h \sin \beta + L_C(\cos \beta - 1)}{\sin 2\beta} \end{cases} \quad (13)$$

Substituting formula (13) into formula (11) (12), we can get

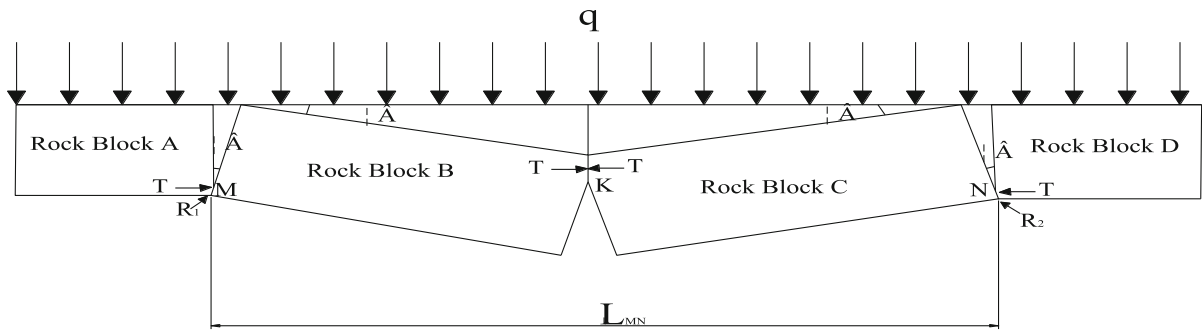


Fig. 7 Mechanical model of main roof breaking

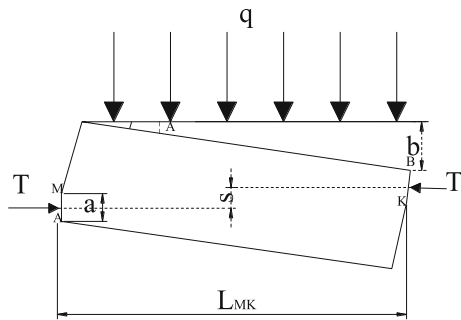


Fig. 8 Stress analysis of key block B

$$T = \frac{q \left(h \sin \beta + \frac{L_C \cos \beta}{2} \right)^2}{2 \left(h \cos \beta - \frac{L_C \sin \beta}{2} - \frac{2h \sin \beta + L_C (\cos \beta - 1)}{\sin 2\beta} \right)} \quad (14)$$

$$\lambda = \frac{h \sin \beta + \frac{L_C \cos \beta}{2}}{2 \left(h \cos \beta - \frac{L_C \sin \beta}{2} - \frac{2h \sin \beta + L_C (\cos \beta - 1)}{\sin 2\beta} \right)} \quad (15)$$

The influence of different thickness h , span L_C and rotation angle β on λ can be obtained from Eq. (15). The analysis shows that λ increases non-linearly with the increase of rock return angle β , but the main roof thickness increases and the span decreases. λ and q gradually show a linear increase relationship, and the corresponding λ value also decreases.

3.2.2 Stability Analysis of Main Roof Hinged Structure

The stability of the “three hinged arch” structure formed after the main roof breaking has a significant impact on the coal rib spalling, roof falling and compressive strength. Therefore, the analysis of its instability characteristics is of great significance for

mastering the law of ground pressure behavior in the working face and determining the reasonable selection of support working resistance.

Since the “three hinged arch” structure is balanced and stable by the friction between the hinge points M and N of the fractured rock mass and the front of the coal rib and the non fractured rock layer behind the goad, the friction at the hinge should not be less than the shear R to maintain the stability of the structure, otherwise the sliding instability will occur. According to the condition of mechanical equilibrium, it is known that the condition of sliding instability is that:

$$T \tan \varphi \leq R \quad (16)$$

In the formula: $\tan \varphi$ is the friction coefficient between rock blocks, generally 0.3, (Zhao et al. 2019); Substituting formula (14) into formula (16), which can be obtained by simplification:

$$R \geq \frac{q \left(h \sin \beta + \frac{L_C \cos \beta}{2} \right)^2 \tan \varphi}{2 \left(h \cos \beta - \frac{L_C \sin \beta}{2} - \frac{2h \sin \beta + L_C (\cos \beta - 1)}{\sin 2\beta} \right)} \quad (17)$$

According to formula (17), the relationship between the thickness h and span L_C and the angle of gyration β is obtained under the condition of sliding instability of the fractured rock block. If the thickness span of the rock block is brought into the formula, when the angle of gyration β is 8° , the sliding instability will not occur.

When the rotation angle β is $0^\circ - 8^\circ$, the ratio of thickness to span should be less than 0.2 when the fractured rock block does not slide and lose stability, and the ratio of limit span to thickness when the main roof rock beam of the fully mechanized top-coal caving face breaks is generally greater than 0.2, so the

articulated rock block is prone to slide and lose stability in the early period of rotation.

4 Numerical Simulation Analysis

In order to further study the breaking law of soft roof in fully mechanized top-coal caving face, the numerical simulation method is used to study the breaking law under different advancing length of working face.

4.1 Model Building

Based on the study of the geological conditions of the fully mechanized top-coal caving face 2–100 in coal seam 2#, a numerical model is established by using UDEC software. The calculation model is 180 m in length and 120 m in width. A vertical stress of 10 MPa is applied at the top of the model to simulate overburden pressure, with a roller boundary along the sides and at the bottom. In order to reduce the influence of the boundary, a transition area of 40 m is reserved on both sides of the model. The left and right boundaries of the model limit horizontal displacement, and the lower boundary limit vertical displacement. The gravity acceleration is 9.8 m/s^2 . The relationship between the initial model and lithology is shown in Fig. 9.

4.2 Roof Breaking Characteristics

The fracture rule of overlying strata is shown in Fig. 10. It can be seen from Fig. 10 that due to the fully mechanized top-coal caving mining, the mining

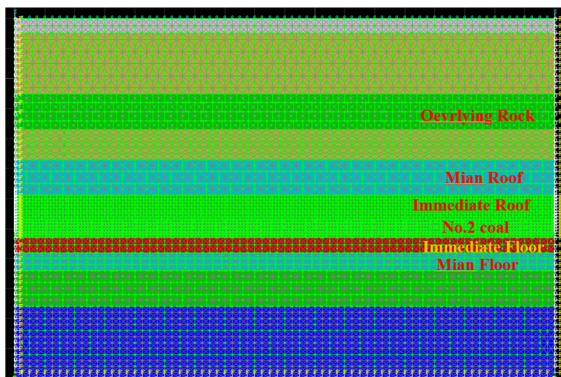


Fig. 9 Numerical model

height of the coal seam is 3 m, the caving height is 2.8 m, and the length of each advancement is 10 m.

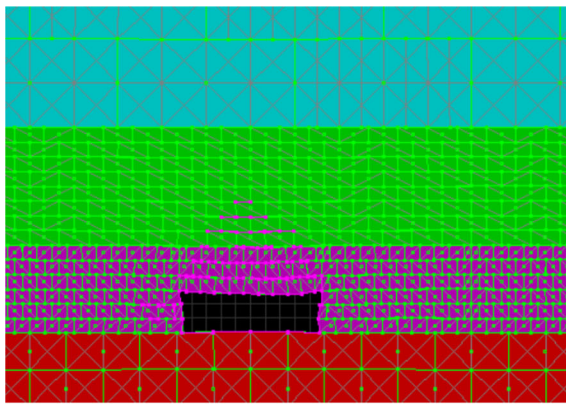
When the working face advances 10 m, obvious cracks appear on the immediate roof. As the working face continues to advance to 20 m, the immediate roof caving. When the working face advances to 40 m, the main roof breaks for the first time, causing the first weighting coming from the working face. Then when the working face continues to advance to 60 m, the main roof breaks again, which is the first periodic weighting coming.

It can be seen from the fracture characteristics of the overlying strata that through numerical simulation, the immediate roof first caving interval of the fully mechanized top-coal caving face 2–100 is 20 m, the first weighting interval of the main roof is about 40 m, and the periodic weighting interval is about 20 m. After the immediate roof is broken, part of the rock blocks fill the goaf, and part of the rock blocks form an “arch” structure. It can be seen in the figure that an “arch” structure is formed every 20 meters. At both ends of the mining, the immediate roof and the coal seam form an “arch” structure formed by the compression of the overlying strata, corresponding to the theoretical analysis.

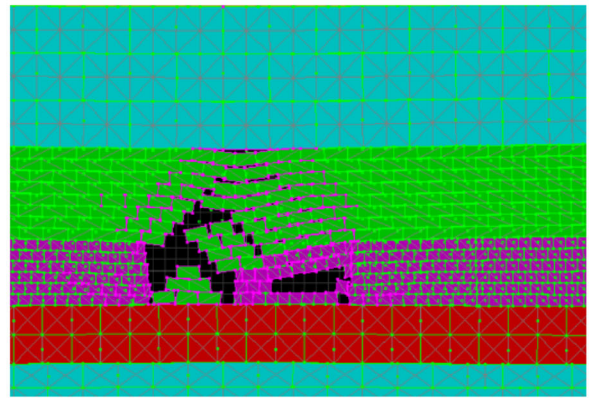
From Fig. 10d, it can be seen that the main roof has separation phenomenon, forming a “three hinge arches” structure. In Fig. 10e, the “three hinge arch” structure is more obvious. In Fig. 10f, it can be seen that the separation phenomenon in Fig. 10e is compacted, and a new separation phenomenon appears.

4.3 Plastic Zone and Stress Distribution of Model

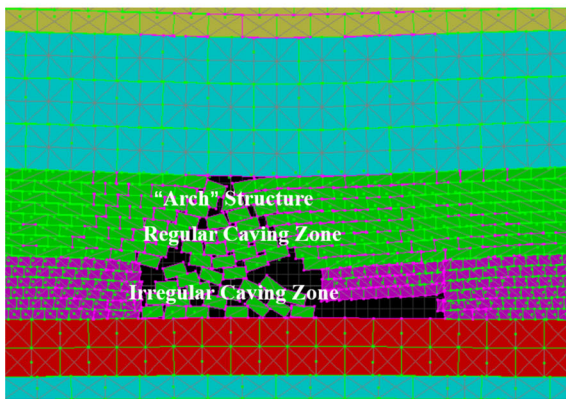
1. When the fully mechanized top-coal caving face 2–100 is advanced for 30 m, there are few fracture areas, small roof subsidence, few cracks in the overlying strata and small plastic failure areas. When the working face advances to 60 m, the red area is reduced, and the deformation and damage area is mainly concentrated in the middle of the goaf. The main roof obviously sinks with the damage of the immediate roof, and the middle of the goaf is also the area with the largest subsidence.
2. With the advance of the working face, the strata above the slope area bear more and more gravity, and the main roof appears a series of movements,



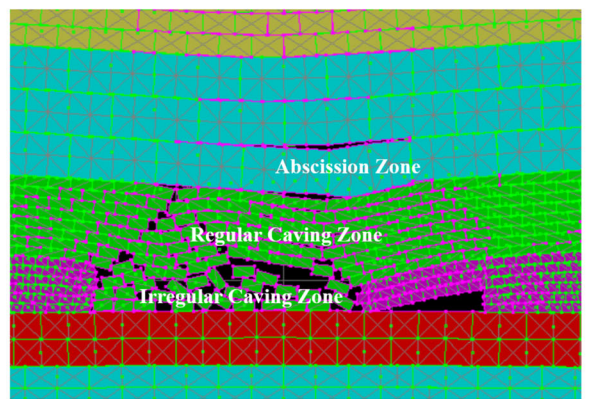
(a) Advance distance: 10m



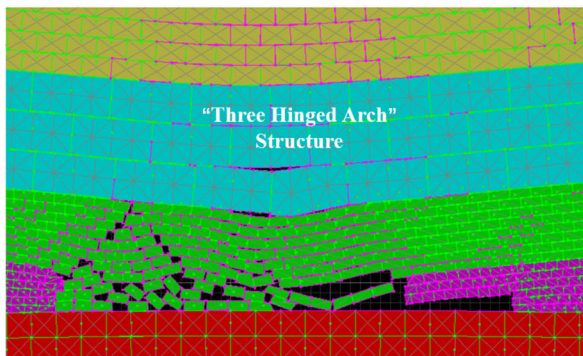
(b) Advance distance: 20m



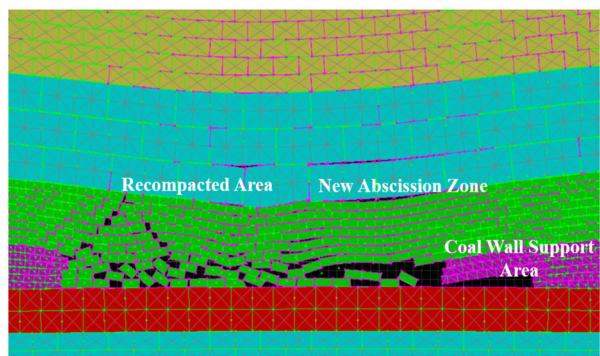
(c) Advance distance: 30m



(d) Advance distance: 40m



(e) Advance distance: 50m



(f) Advance distance: 60m

Fig. 10 Roof breaking characteristics under different advancement distances

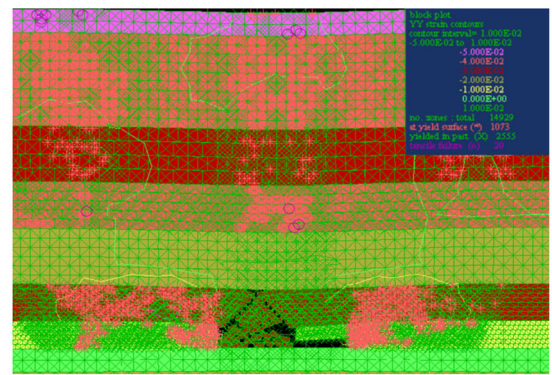
such as deformation, displacement, fracture and failure, resulting in the phenomenon of first weighting. In the Fig. 11, it can be seen that the caving zone, fractured zone, continuous

deformation zone are bodacious, and roof subsidence will increase gradually, and the stress concentration coefficient will increase correspondingly. The higher stress concentration will

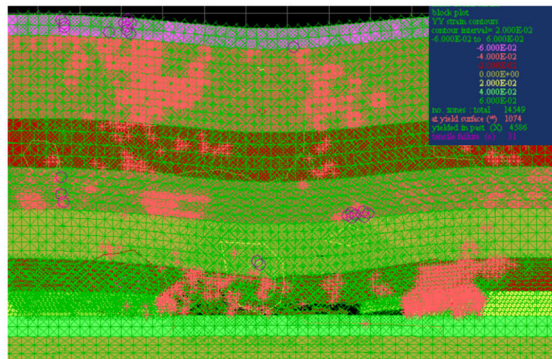
make the overburden caving continue to develop upward, and the caving zone and fractured zone also continue to develop to the depth. When the span of the scope area reaches a certain limit and exceeds the bearing capacity of the strata, it will cause more deformation, fracture and damage of the strata.

- Through the observation of Fig. 11, the stress concentration of surrounding rock appears in front of the coal rib and behind the goad after the coal mining in the working face. With the advance of the working face, the stress concentration coefficient gradually increases and tends to ease, and the stress concentration position moves to the deep part of the coal and rock mass. Moreover, in the goad, it is located in the stress reducing area, and the caved rock mass is gradually compacted and bears the weight of part of the overlying rock mass, so there is a certain stress fluctuation in the goad. When the advancing distance is 80 m, the upward development height of the plastic zone is about 45 m, which is obviously caused by the violent deformation and failure of mud-stone. The 20 m thick medium coarse sandstone in the upper part of the mud-stone has hindered the development of the plastic zone to a certain extent, making it develop slowly.

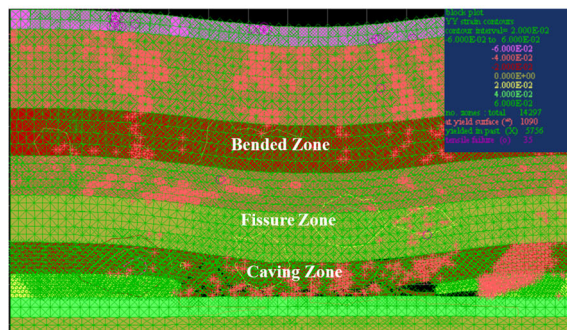
In conclusion, in the place where the stress concentration and energy accumulation, overburden occur plastic deformation and local failure, the thick layer of soft roof, coal and rock strength is low, the coal and rock stored, and limited ability to strain energy accumulated in coal and rock under the action of a mining stress energy is large, damage will occur inevitably produce the hulking expansion deformation, leading to a wide range of mobile strata, coal wall space. Compared with hard rock roof, soft rock roof loose damage range is large, roof deformation is large, large amount of subsidence. With the increase of the advance distance, the “three zones” in the upper strata of the working face are basically formed. When the working face is advanced for 80 m, the failure range of overburden continues to increase, and the plastic zone area increases and gradually penetrates.



(a) Advance distance: 30m



(b) Advance distance: 60m



(c) Advance distance: 80m

Fig. 11 Plastic region and stress distribution diagram of the numerical simulation model

4.4 Roof Subsidence

It can be seen from the figure that the advancing length of the working face is less than 40 m, and there is no obvious continuous deformation phenomenon on the main roof. The advancing length is equal to 40 m, the immediate roof is broken, and the roof subsidence is obviously increased. When the advancing length of the working face is more than 40 m, the main roof has

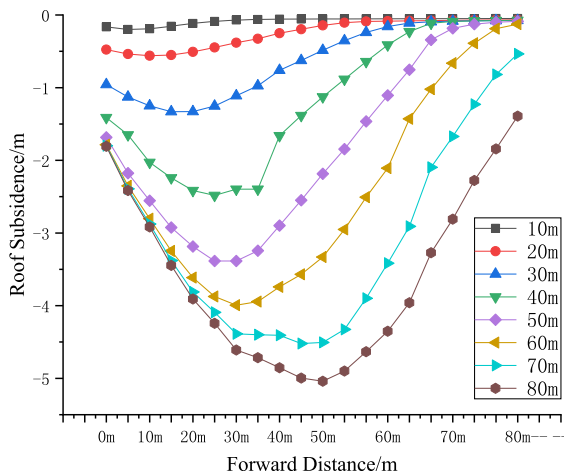


Fig. 12 Roof subsidence curve of different working face propulsion lengths

obvious continuous deformation. The maximum subsidence is generally half of the advancing length, that is, the middle of the goad. When the advancing length is 80 m, the maximum subsidence is 5.04 m (Fig. 12).

To sum up, in the mining of thick coal seam with weak roof, because the coal seam is thick, caving mining is adopted, the roof with different height above the coal seam has different degree and stage roof caving deformation characteristics, the immediate roof first caving, forming “arch” structure. With the continuous advance of the working face, the main roof fracture forms a triple “arch” structure. After the main roof fracture, the roof subsidence gradually increases, the overlying strata obviously sinks, and the continuous deformation zone appears.

5 Engineering Practice

In order to study the broken law of soft thick roof in fully mechanized top-coal caving face, combined with the specific mining engineering and technical conditions of fully mechanized top-coal caving face 2–100, field measurement and ground pressure control technology are carried out.

The roof of the tunnel in the experimental section was monitored three times (20, 40, 60 m away from the excavated section of development) by the borehole detector. The results show that when it is 10 m away from the excavated section of development, the mudstone at 0.2–2.5 m above the roof of the experimental

section and the coal line at 2.2 m above the roof are damaged laterally. When it is 40 m away from the excavated section of development, the fine-grained sandstone at about 8 m above the roof of the experimental section breaks longitudinally, forming a hinged arch. The coal seam line is damaged laterally at about 10.4 m and 12.4 m above the roof. When it is 60 m away from the excavated section of development, the fine-grained sandstone at 9.2 m above the roof of the experimental section breaks longitudinally, forming an articulated arch, and the rock stratum above 10.4 m above the roof is in a stable state.

According to the field measurement results, the first weighting interval of the immediate roof of the fully top-coal mechanized caving face 2–100 is 17.8 m, the first breaking interval of the main roof is 38.9 m, and the periodic weighting interval is 16–18 m. The results of field detection are basically consistent with the results of numerical simulation and theoretical analysis, which verifies that the soft thick roof of the fully mechanized top-coal caving face is broken in stages to form a composite “three-hinged arch” structure.

6 Conclusions

1. According to the specific mining conditions of the fully mechanized top-coal caving face 2–100, the paper analyzes the failure of the weak roof in the face theoretically, builds the failure model of the weak roof, analyzes and obtains the “arch” structure formed by the immediate roof caving, and obtains the instability conditions of the immediate roof “arch” structure. When the arch offset x is greater than 5.1 m, the “arch” structure will lose its stability. The mechanical model of the main roof is built, and the main roof is broken to form a “three hinge arch” structure. Through the stress analysis of the “three hinge arch” structure, the main roof instability is obtained. When the ratio of the thickness of coal seam to the span of the basic roof is less than 0.2, margin is less than 8° , and it is difficult to slide down.
2. According to the study of the geological and mining conditions of fully mechanized top-coal caving face 2–100, the first weighting interval of the immediate roof of fully mechanized top-coal caving face 2–100 is about 20 m, the first fracture

interval of the main roof is about 40 m, and the periodic weighting interval is about 20 m. With the continuous advance of the working face, when the advance length is 20 m, the “arch” structure appears on the immediate roof. When the advancing length is 40 m, the main roof is broken, and the main roof of the “three hinge arch” structure is broken, the roof subsidence gradually increases, the overlying strata obviously sinks, and continuous deformation occurs. When the working face is advanced to 80 m, the “three zones” of strata on the upper part of the working face are basically formed, the failure range of overburden continues to increase, and the plastic zone area increases and gradually penetrates.

3. According to the field measurement data, the first caving interval of the immediate roof is 17.8 m, the first fracture interval of the main roof is 38.9 m, and the periodic weighting interval is 16–18 m, which is similar to the theoretical analysis and numerical simulation results.

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