Paper No. 134

ISMS 2016

Effects of immediate roof thickness on lower sub key strata movement in ends of large mining height panel

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ABSTRACT
Based on the 58 geological drill holes around panel 42105 in the Ordos coal field, a 3D geological model and 2D numerical model with real strata conditions were established. With the models, the effect of the immediate roof thickness on the ground pressure as well as the roof movement patterns under the varying immediate roof thicknesses were explored. Mechanical models of the lower sub key strata under differing immediate roof thickness were achieved through the use of field measurement, theoretical analyses, and numerical simulation methods. Meanwhile the effect of immediate roof thickness on lower sub key strata movement in ends of large mining height coal faces was studied. The discrimination formula of the movement patterns was deduced. The results show that when the immediate roof is relatively thick, the fractured lower sub key strata can be hinged to form a stable "Voussoir Beam" structure, which makes the ground pressure not severe and the shield pressure small in the ends of the panel. When the immediate roof is thin, the arc triangular of the lower sub key strata in the ends of the panel loses mechanical contact to the caved immediate roof and assumes a "Cantilever Beam" structure, which makes the ground pressure severe and shield pressure large in the ends of the panel.
KEYWORDS: immediate roof thickness; large mining height; lower sub key strata movement; ground pressure

1. INTRODUCTION

The mining object is an opaque and changeable geological body. Due to the large spacing among geological exploration drill holes, the changes in rock strata thickness are difficult to find before mining begins. There are many scholars who research the movement patterns of roof strata, mostly based on simplified geological conditions with equal thickness (Yuan et al. 2015; Yang et al. 1999; Fu et al. 2009; Wang et al. 2015; Wang et al. 2014). However, in actual geological bodies, the rock strata are often not of equal thickness. Along with changes in the geological conditions, the movement patterns of the roof strata also change. Thus, it is not accurate to predict the roof strata movement patterns of the whole working face according to data from a single borehole, especially when the thickness of the rock strata varies greatly.

To address this issue, a new method of GMS - ANSYS - CDEM modelling and calculation is put forward, in which a relatively accurate geological model is established based on the geological drill holes data. In order to master the change of the thickness of rock strata, study the determination and prediction of the movement patterns of the roof strata and the modelling of the numerical simulation, the following steps were followed. Firstly, the 3D geological model was established by using the GMS 3D geological modelling software according to the geological drill hole data. Then, the geological model was imported into the ANSYS software to complete the mesh generation. Finally, the node data information of the meshed model was imported into the CDEM simulation software for calculations. As a result, this method makes up for the shortage of CDEM simulation software in modelling and realizes a quick and accurate method for modeling complex geological bodies. The ANSYS - CDEM - GMS modelling and simulation method can reflect the change trend of the rock strata thickness in complex geological bodies, which greatly improves the accuracy and reliability of numerical simulations.

The existing typical patterns of rock strata structure are the "Transferring Beam" structure (Song et al. 2002), "Voussoir Beam" structure (Qian et al. 1995, 1998) and "Key-Layer" theory (Feng et al. 2008; Ju et al. 2011; Shen et al. 2011; Yang 2008). These theoretical analyses demonstrated the several possible movement patterns of rock strata under certain geological conditions. The roof structure is greatly influenced by the change of the overlying rock conditions and mining technical parameters. For the large mining height panel the mining space is relatively large, leading to a great increasing of the caving and fractured zones of the roof strata. When the thickness of the immediate roof is not the same, the filling degree of the caved immediate roof for the gob will be different. Eventually, the overlying strata movement patterns and the ground pressure distribution are changed (Huang

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2005; Huang et al. 2004; Wu 2014; Zhang et al. 2013). Based on the geological conditions of panel 42105 and the recorded data of shield pressure and the 3D geological model, the current study researched the formation mechanism of the mechanical structure of the lower sub key strata under the large mining height, and deduced the calculation formula of the movement patterns.

2. BACKGROUND

2.1 Panel overview

The width of panel 42105 is 230 m, with an average depth of 440 m. Using the caving coal mining method, it has 3.7 m cutting height and 3.0 m top coal caving height. Panel 42105 is covered with the upper gob of 2-2 coal seam.

2.2 3D geological model

In order to grasp the thickness of the overlying strata in the 42105 working face, the GMS geological modelling software was used to establish the 3D geological model of panel 42105 on the base of the 58 geological drill hole data around this panel, and made the tailgate profile along the advancing direction.

According to the 3D geological model, the thickness of the immediate roof varies greatly. The immediate roof sandy mudstone along the working face advancing direction first follows a thinning and then thickening trend. The profiles were exported to CAD format and then the strata thickness was measured. The immediate roof thickness gradually reduced from 6.2 m to 4.3 m in the first 280 m. The immediate roof thickness gradually thickened to 5.6 m during the advancing distance between 280 m and 350 m. The thickness of the lower sub key strata changed little, with an average of 10.2 m.

3. IMMEDIATE ROOF THICKNESS AND STRUCTURE

In the process of coal mining, the shape and stability of mechanical structure formed by the lower sub key strata directly affects the distribution of the ground pressure in the working face. The typical research findings are the “Voussoir Beam” and “Kichhoff Plate” mechanics models (Qian et al. 1995; Zhu et al. 1987). According to the breaking rules of overlying rock, the periodic fracture rocks of the lower sub key strata can form the “Voussoir Beam” structure in the middle part and arc triangular structure in the end region of the panel (Figure 1) (Qian et al. 1998). The thickness of the immediate roof and lower sub key strata determine the structure movement patterns of the broken rocks. The ground pressure in the panel ends region is mainly affected by the deformation motion of the rock C and arc triangular A, of which the arc triangular A is the main part (Yang et al. 2012).

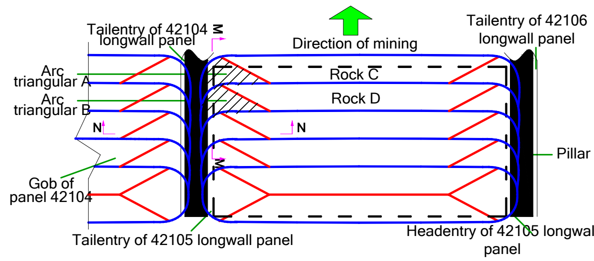
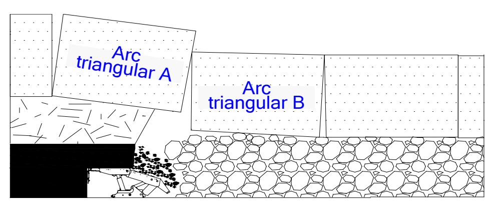


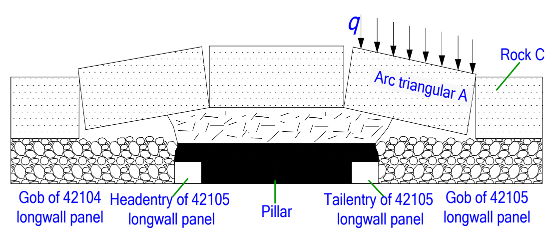
Figure 1: Schematic diagram of the broken form of the lower sub key strata.

3.1 Steady rock structure

When the immediate roof is thick, the caved immediate roof can basically fill the gob. Rock B, C, D, and arc triangular A form the “Voussoir Beam” structure, in which the rock C is the key block in the middle part of the panel. As shown in Figure 2, due to the hinge relationship among rock A and B, C, D, the sliding and rotational deformation instability will not happen for arc triangular A.



(a) M-M profile



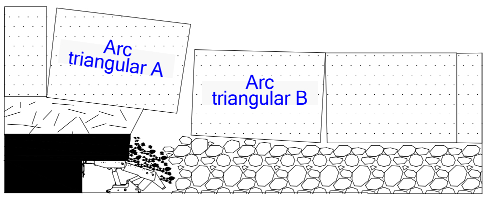
(b) N-N profile

Figure 2: “Voussoir Beam” structure (thick immediate roof).

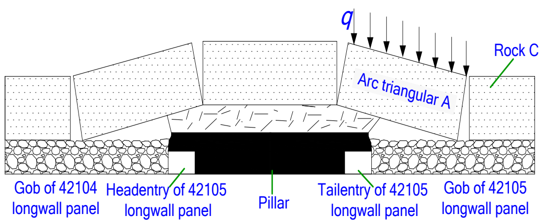
3.2 Instable rock structure

When the immediate roof is thin, the caved immediate roof cannot fill the gob. Arc triangular A loses the mechanical contact among rock B, C, D, and the “Voussoir Beam” structure cannot be formed, but instead turns into a hanging plate between the coal walls (Figures 1 and 3). Since a structure with carrying capacity cannot be formed from arc triangular A, the pressure of the rock strata in the ends region is mostly transferred to the shield and the roof of gateroads.

When the arc triangular A experiences sliding instability, the ground pressure in the ends of panel is severe.



(a) M-M profile



(b) N-N profile

Figure 3: "Cantilever Beam" structure (thin immediate roof).

3.3 Calculation of roof structure movement

An arch structure is formed after the caving of lower sub key strata. When the hinge at the arch center is higher than those of the two ends, the rock block can maintain equilibrium. When the center hinge and those at the two ends are in the same plane, the rock block reaches the state of limit equilibrium, as shown in Figures 4 and 5. In view of the plastic state of the hinge point, the contact length of the unit width of the rock mass is a, the failure condition for any rock strata above the coal seam can be solved and the limit of subsidence Δ_{max} determined (Jiang, 2015).

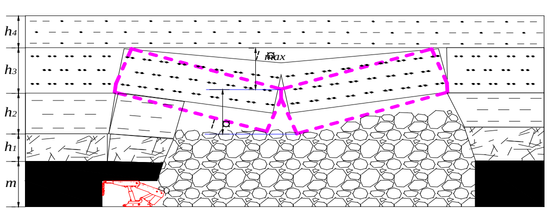


Figure 4: Schematic failure of lower sub key strata.

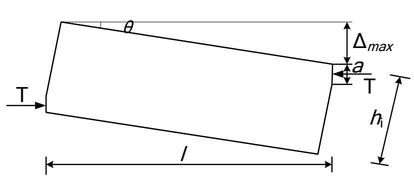


Figure 5: Limit equilibrium condition when the hinge contacts of rock blocks are in plastic state.

$$a = \frac{1}{2}\left(h_i - l\sin\theta\right) \quad (1)$$

$$T = \frac{ql^2}{h_i - l\sin\theta} \quad (2)$$

Extrusion stress at the hinged points can be determined by:

$$\sigma_p = \frac{T}{a} = \frac{2ql^2}{\left(h_i - l\sin\theta\right)^2} = \frac{2qi^2}{\left(1 - i\sin\theta\right)^2} \quad (3)$$

Where, $i=l/h_i$.

Let the ratio of bearing strength σ_p to compressive strength σ_c be K_1, the maximum allowable load q can be determined by:

$$q = \frac{K_1\left(1 - i\sin\theta\right)^2\sigma_c}{2i^2} \quad (4)$$

When the beam is at ultimate fracture span, the relationship between its load q and tensile strength σ_t can be determined by:

$$\sigma_t = K_2 q\frac{6l^2}{h_i^2} = 6K_2 qi^2 \quad (5)$$

Where:

a= Contact length of broken rock block, m;

θ= Rotation angle of broken rock block, °;

T= Horizontal force required to keep the limiting state, Pa·m;

h_i= Thickness of i[th] rock layer above the coal seam, m;

l= Broken interval of i[th] rock layer above the coal seam, m;

q= Weight and load of i[th] rock layer above the coal seam, Pa;

K_2= General value 1/3 ~ 1/2;

n= Ratio of compressive strength σ_c to tensile strength σ_t.

Limit of subsidence Δ_{max} can be determined by:

$$\Delta_{max} = h_i\left(1 - \sqrt{\frac{1}{3nK_1K_2}}\right) \quad (6)$$

Where, $\Delta_{max}=l\sin\theta$.

After the failure of the immediate roof, the subsidence of lower sub key strata Δ_{hi} can be determined by:

$$\Delta_{hi} = m - \left(K_p - 1\right)\sum h \quad (7)$$

Where:

m= Mining height, m;

K_p= Bulking factor;

σ_{ci}= Compressive strength of i[th] rock layer above the coal seam, Pa;

$\sum h$= Thickness of the first to (i-1)[th] rock layer above the coal seam, m.

Using the overburden strata mechanics parameters of Panel 42105 (K_p=1.25, $\sum h$=4.1～6.2m), the Δ_{hi} of lower sub key strata can be determined between 5.15 m and 5.68 m.

According to Kong et al. (2010), there is a relationship between the extrusion stress σ_p and compressive strength σ_c of the rock block at the hinge point: σ_p=0.36～0.45σ_c. Generally σ_p=0.4σ_c is used. According to the simply supported beam model, K_2=1/3, the ratio of compressive strength σ_c to tensile strength σ_t of siltstone is 12 in panel 42105. Therefore, the limit of subsidence Δ_{max}=5.54 m.

Compared to the subsidence of lower key strata Δ_{hi} and the limit of subsidence Δ_{max}, when the immediate roof is more than 4.64 m, the fractured lower sub key strata can form a stable "Voussoir Beam" structure; when the immediate roof is less than 4.64 m, the fractured lower sub key strata will assume a "Cantilever Beam" directly baggy falling form.

3.4 Numerical simulation

Based on the 3D geological model established by the GMS software，a numerical model was built to simulate the geological cross-section along the panel advancing direction. The model was 400 m long by 464 m high. The model contained the full overburden thickness from the coal seam to the surface. The vertical loading was the full overburden gravity load and the boundaries of the bottom, left and right sides of the model were fixed. CDEM (Continuum-based Distinct Element Method) software was used to calculate, in which the Mohr-Coulomb strength criterion was chosen as the material yield criterion of coal and rock mass. By the numerical calculation results, the change of the lower sub key strata structure during the mining process was analyzed with the thickness change of the immediate roof.

(1) Thin immediate roof

When the face has advanced 270 m, the immediate roof is 4.34 m. Simulation results show that the caved immediate roof cannot basically fill the gob. The arc triangular of the lower sub key strata in the ends of the panel lost mechanical contact to the caved immediate roof. The original lower sub key strata can be formed with a load-bearing structure due to the increasing of rotation angle, forming a "Cantilever Beam" structure (Figure 6).

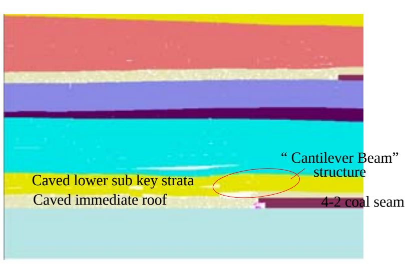


Figure 6: "Cantilever Beam" structure (270 m advancing).

(2) Thick immediate roof

When the face has advanced 230 m, the immediate roof is 4.81 m. Simulation results show that after the lower sub key strata caving, the broken rock can hinge to each other and form the "Voussoir Beam" structure (Figure 7). Compared to the results of "Cantilever Beam" structure, the vertical displacement range of the upper strata and coal seam is relatively small at this time.

Figure 7: "Voussoir Beam" structure (230 m advancing).

4. SHIELD DATA ANALYSIS

Panel 42105 was equipped with an electric hydraulic control monitoring system that can automatically and quickly upload the shield pressure to the ground control room. Surfer 8.0 was used to draw the 3D map of the relationship among working face, shield pressure, and advancing distance from June 16th - 23th (Figure 8).

Since roof pressure usually varies continuously with time, time-weighted average pressure (TWAP) is more appropriate to illustrate the overall conditions of the shield in a whole cycle and is defined by the following equation (Syd S. Peng, 2013; 2011):

$$P_t=\frac{\sum P_i t_i}{t_t}=\frac{\frac{1}{2}(P_a+P_s)t_a+\frac{1}{2}(P_b+P_a)t_b+\frac{1}{2}(P_c+P_b)t_c+\frac{1}{2}(P_d+P_c)t_d}{t_a+t_b+t_c+t_d} \qquad (8)$$

Where, P_i is the average shield pressure during the period of t_i. In other words, P_t is the ratio of the area under the pressure variation curve to the total time in a mining cycle.

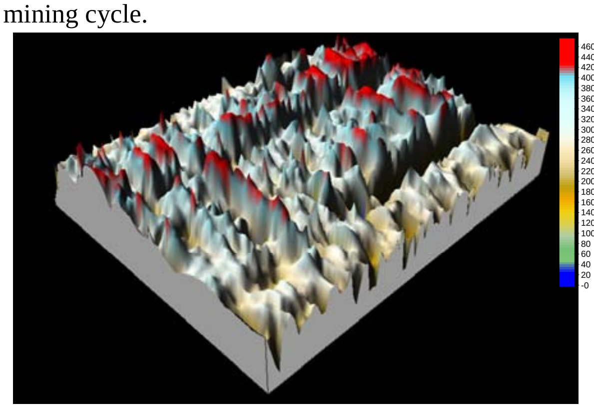


Figure 8: 3D map of the relationship among working face, shield pressure, and advancing distance.

The TWAP and standard deviation of 100# shield near the tailgate was analyzed in the panel 42105 from June 16th - 28th (Table 1). The results show that: (1) The TWAP and standard deviation of 100# shield were floating large on June 17, 19, 21, 22, (due to the working face being off production on June 18th, the shields weren't moved, resulting in great pressure on the roof), indicating great intensity of the roof strata activity. In these days, 70% of the all shields opened the yield valve, meanwhile the rib spalling was serious, with an average depth of 0.3 m. (2) When the immediate roof thickness decreases, the TWAP and standard deviation increase. On June 22th, the immediate roof thickness was the smallest and the standard deviation reached the maximum of 10.90 MPa. When the immediate roof thickness increases, the TWAP and standard deviation decrease.

Table 1: TWAP and standard deviation of 100# shield at different advancing distance.

Date	Pt/ MPa	σ/MPa	(Pt+σ)/ MPa	Advancing distance/m	Immediate roof thickness /m
6.16	29.39	5.38	34.77	218.6	4.84～4.98
6.17	29.41	6.30	35.71	236.5	4.64～4.84
6.18	37.04	7.91	44.94	239.2(Off production)	4.61～4.64
6.19	36.02	9.87	45.89	250.9	4.47～4.61
6.20	29.29	3.46	32.76	251.7(Off production)	4.46～4.47
6.21	29.29	6.14	35.43	266.0	4.32～4.46
6.22	26.58	10.90	37.48	278.5	4.16～4.32
6.23	28.78	3.65	32.43	289.0	4.16～4.76
6.24	28.96	5.27	34.23	301.6	4.76～4.92

When the immediate roof is thick, the lower sub key strata actual subsidence is less than its limit subsidence, the fractured lower sub key strata can be hinged to form a stable "Voussoir Beam" structure. This structure bears part of its own weight, so that the weight of the rock on the shields is reduced. When the immediate roof is thin, the lower sub key strata actual subsidence is more than its limit subsidence. The arc triangular of the lower sub key strata in the ends of the panel loses mechanical contact to the caved immediate roof and assumes a "Cantilever Beam" structure. Therefore, the most weight of the lower sub key strata through the immediate roof directly acts on the shield, which makes the shield pressure large in the ends of the working face.

The influence factors of the shield pressure are related not only to the thickness of the immediate roof and the movement patterns of the lower sub key strata, but also to the shield frame, the advancing speed, and the mining height. However, the above data analysis shows that there is a correlation between the change of shield pressure and the immediate roof thickness. That is, when the immediate roof becomes thin, the TWAP and standard deviation show an increasing trend, and vice versa.

5. CONCLUSIONS

This paper concentrates on the effect of immediate roof thickness on the lower sub key strata movement in the ends of panels. A 3D geological model was established and used to deduce the formula of the movement patterns of roof structure under different immediate roof conditions, and analyzed the numerical simulation results and the monitoring data of the shield pressure. The following conclusions were obtained:

(1) When the thickness of the lower sub key strata changes little, the immediate roof thickness is an important factor that affects the structure and the ground pressure distribution.

(2) Compared to the actual subsidence of lower key strata Δ_{hi} and its limit subsidence Δ_{max}, when $\Delta_{hi}<\Delta_{max}$, a stable "Voussoir Beam" structure can be formed in the fractured lower sub key strata; when $\Delta_{hi}>\Delta_{max}$, the lower sub key strata assumes a "Cantilever Beam" structure.

(3) The stable "Voussoir Beam" structure bears part of its own weight, so that the weight of the rock on the shields is reduced and ground pressure is not severe, and the TWAP and standard deviation is small. Under the "Cantilever Beam" structure conditions, the most weight of the lower sub key strata through the immediate roof directly acts on the shield, which makes the ground pressure severe and TWAP and standard deviation large.

6. ACKNOWLEDGMENT

This research was funded by the Chinese Natural Science Committee under grant No. U1261207.

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