

# Analysis of the top coal stability of the large section open-off cut under the gob in thick seams slicing mining

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## Article

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# Analysis of the top coal stability of the large section open-off cut under the gob in thick seams slicing mining

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**Abstract:** The reserved thickness of top coal has an important influence on the stability of a large section open-off cut under gob in the thick seams slicing mining. The destabilization extremum conditions of the open-off cut top coal were derived from by elastic-plastic theory, and the optical fiber sensing technology was utilized to monitor the top coal deformation law with different thicknesses (3, 3.5, and 4m) in the physical similar simulation experiment in the paper. The results show that the top coal thickness is greater than 3.4m without tension cracks. In the vertical direction, the top coal of the LSOOC is divided into mining and excavation disturbance zones under the influence of the upper slice coal mining and the excavation disturbance. In the direction of the span of the open-off cut, the top coal can be divided into the roof fall risk zone and the warning zone. The deformation changes from exponential to linear to logarithmic in the roof fall risk zone, and it changes from linear to logarithmic in the roof fall warning zone as the number of excavations increases. The sinking amount in the two zones is smaller as the thickness of the top coal becomes larger. It is comprehensively determined that the thickness of the top coal of open-off cut is set as 3.5m, the stability is moderate, and the field application shows that the integrity of the top coal is good after support, and the maximum off-layer value is 6mm, which can satisfy the production requirements.

**Keywords:** Thick coal seam, Slice mining, Large section open-off cut, Thickness of top coal, Optical fiber sensing;

## 1. Introduction

The maximum minable thickness of the coal seam is up to 12.5 m in the Yushenfu mining area in Northern Shaanxi, China. Due to the limitation of the technical level, layered mining technology is adopted for mining in the early stage of resource development[1]. Influence of nearby small kiln cross-border mining and geological structure and other factors, the open-off cut has to be laid below the mining gob when the lower slice coal resources mining. With the increase in mine production and the enlargement of fully mechanized mining equipment in recent years, the section of the open-off cut has continuously enlarged, and it is more difficult to control the stability of the surrounding rock[2][3][4].

To analyze the stability of the open-off cut roof, scholars simplified the roof as a beam through the method of theoretical analysis to investigate the stability[5][6]. The mechanical structure model of the continuous beam under a uniformly distributed load was established by Jiang et al to obtain the stress distribution law in the cut roof rock layer under roadway mining[7]. The maximum deflection and rotation angle of mining roadway under three different combined structures of roadway broken roof rock mass beam, fixed support beam, and the composite beam was deduced by Yao et al and discussed the relationship between roadway width, interlayer thickness, mining height of upper coal seam and roof deformation[8]. The mechanical model of fracture instability of long-span open-off cut was proposed by Jia et al and analyzed the instability and collapse form of the roof **Error! Reference source not found.**

As for the deformation law and support technology of the open-off cut surrounding rock, He et al conducted a systematic study on the relationship between the width of the open-off cut and stress and deformation. The result shows that the larger the width, the smaller the shallow partial stress in the roof of the cut, the larger the deep partial stress, and the value of partial stress gradually decreases and shifts to the deep. The peak of the main stress difference in the roof is constant and then decreases, it is first decreased and then constant on the floor. there is a gradually increasing trend in the two sides of the open-off cut hole **Error! Reference source not found.****Error! Reference source not found.** The fracture field of the surrounding rock of the open-off cut is divided into fracture penetration zone, fracture development zone, and microfracture zone. In addition, with the increase in the width of the open-off cut, the evolution process from the microfracture zone to the fracture development zone and the fracture development zone to the fracture penetration zone of the roof is promoted **Error! Reference source not found.** Furthermore, the top coal plastic zone is rectangular when the thickness of the top coal is small 6m, it is arch-shaped when the thickness is larger than 6m. With the increase of the width of the open-off cut, the roof pulling damaged area increases in an approximately linear relationship, and the deformation dividing point of a fast and slow decline in the top coal gradually rise **Error! Reference source not found.**

Zhao et al found that the range of the plastic zone of the surrounding rock is expanding with the increased width of the roadway, and the displacement on the two sides of the roadway changes slowly, but roof falling capacity increases significantly, and the location of maximum deformation appears in the middle position of the roof **Error! Reference source not found.** Wang et al studied the deformation characteristics of the surrounding rock of the large section open-off cut with a composite roof and found that the top and bottom locations of the open-off cut and the roof are easy to damage, and the damage during the expansion of the open-off cut significantly exceeds the period of the excavating **Error! Reference source not found.**

In the aspect of large section open-off cut support technology, Sun et al studied the support technology of open-off cut under compound roof conditions of large buried depth three soft coal seams, and proposed the joint support technology of high-strength anchor rod anchor network add long and short anchor cable joist to reinforce the surrounding rock, which achieved a good effect of surrounding rock control **Error! Reference source not found..** He et al researched the reasonable configuration of anchor cables for large cross-sectional open-off cut support and proposed the "cross-stepping" joint control technology, which was successfully applied in the field **Error! Reference source not found..** Jia et al proposed a roof zoning control technology with the anchor rod support, and clarified the control principle of different roof zoning for the problems of poor self-stabilization, violent deformation and difficult support of deep large-span open-off cut roof **Error! Reference source not found..** In order to solve the problem of roof support for soft and thick coal seams in extra-thick sections, Yan Hong et al. proposed a control system of twice forming the roadway with evenly divided sections and "multiple support structures", and calculated the safety zoning and safety evaluation factors of the roof of extra-thick coal seams **Error! Reference source not found..**

Overall, there are more findings on the deformation of large section open-off cuts. But the influence of the top coal thickness on the stability of the roof for large section open-off cut under slicing mining conditions is few reports. How to ensure the stability of the surrounding rock of the open-off cut while minimizing the top coal retention thickness is the focus of research on the stability of the open-off cut under such conditions. It not only improves the recovery rate of the remaining coal resources but also reduces the amount of open-off cut excavation work. In this paper, The methods of theoretical calculation and physical similarity simulation experiment were utilized to study the reasonable reserved thickness of top coal. A novel optical fiber sensors technology was used to monitor the deformation law of top coal with three groups of different thicknesses in the experiment. The findings are to provide the scientific basis for the top coal retention of the open-off cut under analogical conditions.

## **2. Calculation of the reasonable top coal thickness**

### **2.1 Engineering background**

Daliuta coal mine is a super large modern mine located in Daliuta Town, Yulin City, Shaanxi Province, China. It is composed of Daliuta and Huojitu minefield with an annual output of 33Mt. The average coal thickness and the buried depth of 1-2 coal of the Huojitu minefield are 10m and 76m. Due to the large thickness of the coal seam and the limitation of mining equipment in the early years, the layered mining method was applied in the 1-2 coal. The design mining height of the upper layer is 4.5 ~ 5m. The remaining 5m thick coal seam is retained under the upper layered gob, and the coal resources remain exceed 30 million tons in the area. The lower 12203 open-off cut is arranged at the lower part of the gob 146 m southeast of the upper 12203 cut affected cross-boundary mining of small coal kiln of 2-2 coal. It is 9 m wide, 3.9 m high, and 251.4 m long, (shown in Figure 1). The total excavation quantity is up to 302.4 m. The top coal thickness is increased by cutting the floor in the excavation process, and the support is strengthened to ensure the stability of the top coal to prevent the open-off cut from connecting with the upper gob. Therefore, determining the reasonable reserved thickness of top coal is the core problem to ensure large section cutting under similar conditions.

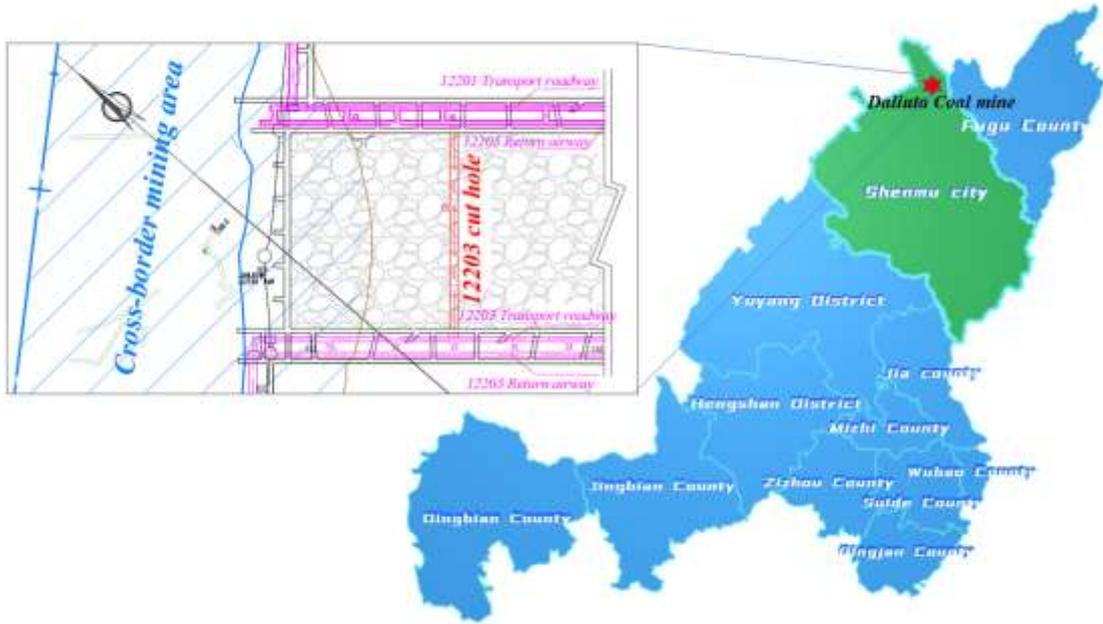


Fig1.The location of working face 12203 of Huojitu minefield, Shaanxi, China

## 2.2 The internal force distribution of top coal

Based on the top coal shape and supporting stress characteristics of the lower 12203 open-off cut, the top coal of the open-off cut can be simplified as two span fixed support beam, as shown in Figure 2.

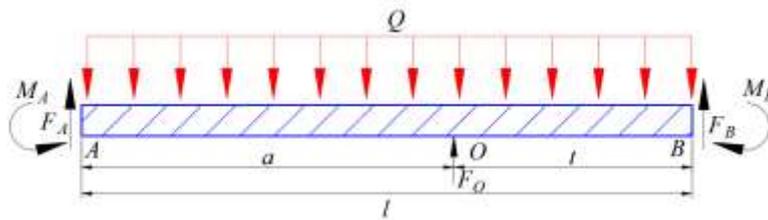


Fig.2 Loading form of top coal

In Figure 2, the resultant force of fulcrum reaction and single hydraulic strut is  $F_A$  and  $F_B$ . The net load on top coal is  $Q$ ,  $MPa$ .  $l$  presents the width of the roadway,  $m$ ;  $F_B$  is the support reaction force of single hydraulic prop,  $KN$ .  $M_A$ ,  $M_B$  is the bending moment in the roadway side,  $KN \cdot m$ .  $a$  is the distance between left side of roadway and single hydraulic strut,  $m$ .  $t$  is the distance between right side of roadway and single hydraulic prop,  $m$ .

The unit step function **Error! Reference source not found.** is introduced to calculate the distributed internal force along the width direction of open-off cut.

$$\mu(x - \xi) = \begin{cases} 0 & (x < \xi) \\ 1 & (x \geq \xi) \end{cases} \quad (1)$$

The unit step function is represented by the step polyline in Figure 3:

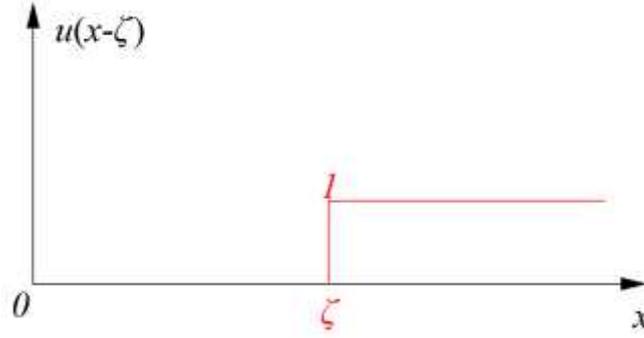


Fig.3 The unit step function

Based on the unit step function, the bending moment, rotation angle and deflection equations of the top coal continuously distributed in the width direction of the open-off cut are to be obtained.

$$EI \frac{d^2 \omega}{dx^2} = M_A + F_A x + \mu(x-a) F_o t - \frac{1}{2} Q x^2 \quad (2)$$

$$EI \frac{d\omega}{dx} = M_A x + \frac{1}{2} F_A x^2 + \mu(x-a) \frac{1}{2} F_o t^2 - \frac{1}{6} Q x^3 + C \quad (3)$$

$$EI \omega = \frac{1}{2} M_A x^2 + \frac{1}{6} F_A x^3 + \mu(x-a) \frac{1}{6} F_o t^3 - \frac{1}{24} Q x^4 + Cx + D \quad (4)$$

According to the boundary conditions: when  $x=0$  or  $x=l$  :  $\omega' = 0$ ,  $\omega = 0$ , substituting the results into equations (3) and (4), and the solution is:  $C = 0$ ,  $D = 0$ ; At the same time,  $M_A$  and  $F_A$  are to be got, and the results are substituted into equation (2), and the bending moment distribution equation along the width direction of top coal is obtained:

$$M(x) = \left\{ \begin{array}{l} \frac{1}{l} F_o t^2 - \frac{1}{l^2} F_o t^3 - \frac{1}{12} Q l^2 \\ + \left( \frac{2}{l^3} F_o t^3 - \frac{3}{l^2} F_o t^2 + \frac{1}{2} Q l \right) x \\ - \frac{1}{2} Q x^2 + \mu(x-a) F_o t \end{array} \right. \quad (5)$$

Based on  $F_s = \frac{dM(x)}{dx}$ , The shear equation of is obtained

$$F_s(x) = \left\{ \begin{array}{l} \frac{2}{l^3} F_o t^3 - \frac{3}{l^2} F_o t^2 + \frac{1}{2} Q l - Qx \\ + \mu(x-a) F_o \end{array} \right. \quad (6)$$

### 2.3 The extreme conditions of top coal instability

Based on the principle of natural equilibrium arch and limit equilibrium **Error! Reference source not found. Error! Reference source not found. Error! Reference source not found.**, the equilibrium state of the original rock stress of the road is destroyed during roadway excavation, and the stress is redistributed. The limit equilibrium is reached when the collapse angle  $\theta = \frac{\pi}{4} - \frac{\varphi}{2}$ . It is not considering the support influence; a limit pressure cycle is to be formed along with a certain range around the

roadway. The relative position relationship between the loop line and the roadway is shown in Figure 4.

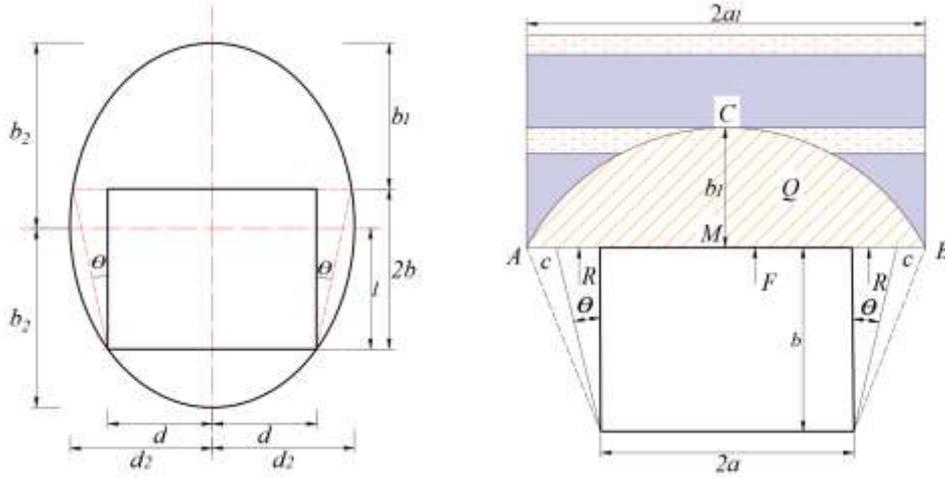


Fig.4 Relative position of limit equilibrium arch and roadway

The self weight stress of rock in arch can be obtained in the formular (7):

$$Q_k = \gamma \left( l + \frac{d_2}{\sqrt{\lambda}} - 2b \right) \quad (7)$$

The collapse arch height is:

$$b_1 = l + \frac{d_2}{\sqrt{\lambda}} - 2b \quad (8)$$

In the above formular:  $l = \frac{d \tan \theta + b(\lambda + \tan^2 \theta)}{\lambda}$ , the length of short half axis of pressure arch is  $d_2$ ,

$d_2 = \sqrt{d^2 + l^2}$ , the collapse angle is  $\theta = \frac{\pi}{4} - \frac{\varphi}{2}$ , the average unit weight of rock in the collapse zone is

$\gamma = 23 \text{KN} / \text{m}^3$ ,  $\varphi$  is the coal friction angle, taken as  $28^\circ$ ,  $\lambda$  is the side pressure coefficient, taken as 0.8,  $d$  is half of the width of the open-off cut, taking 4.5m;  $2b$  is the cutting height, taken as 3.9m.

The parameters mentioned are substituted into equation (7) (8). When the top coal is not considered, the results are calculated as follows: the caving rock load  $Q_k$  in the gob and the arch height  $b_1$  are 0.25MPa and 10.9m.

Clearly, the arch height is much greater than the traditional anchor cable support length. Therefore, reserving appropriate top coal thickness, giving full play to the active support role of bolt (cable) and improving the bearing capacity of top coal are the key to ensure the roof stability of the lower open-off cut.

The bending moment and shear force distributed along the width of top coal is to be got by taking  $Q=Q_k=0.25\text{MPa}$  into equations (5) and (6).

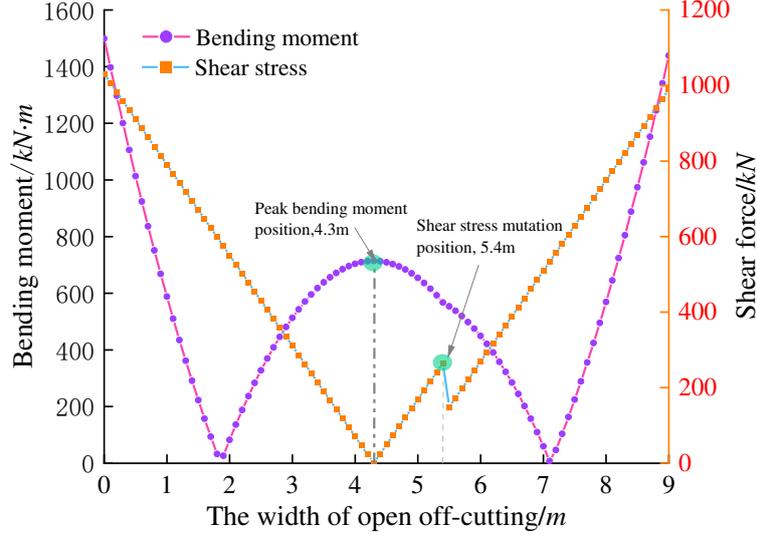


Fig.5 Distribution of bending moment and shear force along coal beam

As shown in Figure 5, the peak bending moment is located at both ends and the middle of the top coal. That is, the top coal both ends and the mid bottom are influenced by pull stress during the open-off cut excavation. Where through tension crack probably is generated, and rotation trend of the top coal towards the mined space is produced. After that, the stability of the damaged top coal is mainly controlled by the friction between the through cracks.

Influenced by the supporting effect of the single hydraulic prop in the open-off cut, the peak positions of bending moment and shear force are offset to the left side, which is a large distance side between the single hydraulic prop and the roadway side. The maximum peak values of bending moment and shear force appear at the position of  $x = 0$ . When the top coal does not produce tension cracks under the influence of the dead weight of the top coal, the following formula shall be met:

$$\frac{6M_{max}}{bh^2} = \left| \frac{6}{h^2} \left[ \frac{F_o t^2}{lb} - \frac{F_o t^3}{l^2 b} - \frac{Q_k l^2}{12b} \right] - \frac{\gamma l^2}{2h} \right| \leq \sigma_t \quad (9)$$

The top coal does not slip along the through crack, the following formula needs to be met:

$$\frac{F_{smax}}{bh} = \left| \frac{1}{h} \left( \frac{2F_o t^3}{l^3 b} - \frac{3F_o t^2}{l^2 b} + \frac{Q_k l}{2b} \right) + \frac{1}{2b} \gamma l \right| \leq \sigma \tan \varphi \quad (10)$$

Where:  $b$  is the width of the coal beam, taking the unit length is 1m;  $\sigma_t$  is the tensile strength of coal seam, taking 0.8MPa,  $\sigma$  is the horizontal stress, taking as 1.5MPa.

The relationship between the maximum tensile stress and shear stress and the thickness of top coal is shown in Figure 6:

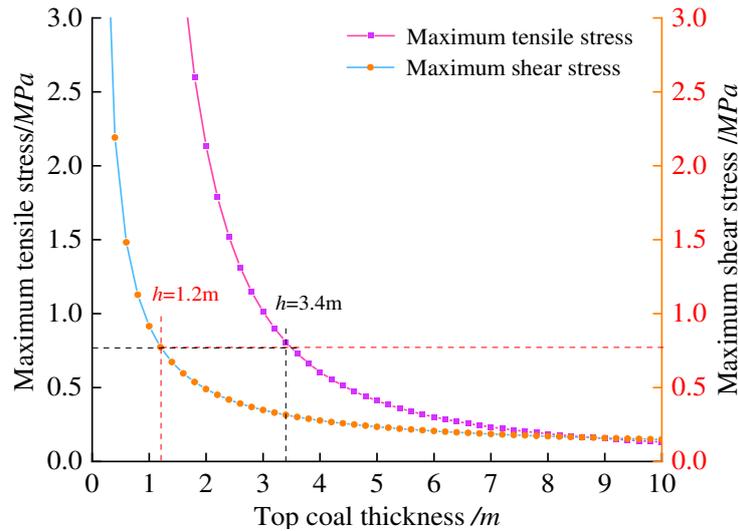


Fig.6 Variation of maximum tensile and shear stress with top coal thickness

It can be seen from Figure 6 that the maximum tensile stress and shear stress decrease rapidly with the increase of top coal thickness, indicating that the greater the top coal thickness, the more stable it is. However, the thickness of the top coal is too large, and the greater the undercover amount during the open-off cut excavation, which is unfavourable to the mining working face.

Therefore, it can be considered that the top coal does not produce through cracks, which can meet the production demand. Substituting the relevant parameters mentioned above into equation (9) (10). It is calculated that when the top coal thickness is greater than 3.4m, the top coal does not produce through tension cracks. The broken top coal does not slide along the penetrating crack when the thickness of the top coal is greater than 1.2m.

### 3. Physical similarity simulation experiment of reasonable top coal thickness reservation

The lower 12203 open-off cut is located under the gob, and the roof fissures are developed affected by the upper 12203 working face mining. In addition, the section of the open-off cut is large, which is difficult to support, and roof caving is easy to occur. The top coal thickness of the lower 12203 open-off cut is theoretically analysed in section 2 to ensure the safety of cutting excavation and production. To determine the optimal top coal thickness, the deformation characteristics of different top coal thicknesses and the stability of surrounding rock of the large section cutting are to be investigated with a similarity simulation.

#### 3.1 Similarity model design

Based on the thickness of 1-2 coal seam and overlying strata are 9.96 m and 76 m. A similarity simulation experiment with length 3.0m, width 0.2m, and height 1.99m is designed. The geometric similarity ratio, the bulk density, stress, and time similarity constant of the model are 1:50, 1.56, 78, and 7.1. Limited by the height of a simulation test frame, No.13 ~ 19 rock formations are not built above the 1-2 coal seam. The loading of lack rock formation is loaded with iron brick, so the actual height of the physics model is 1.26m. Meanwhile, river sand, fly ash, mica, gypsum, white powder, and water are used to prepare similar materials in a certain proportion. The detailed ratio is shown in Table 1.

Table 1 Ratio of similar materials

No.	Lithology	Proportion number	Slice Thickness/cm	Total Thickness/cm	Gypsum/kg	Calcium carbonate/kg	Pulverized Coal/kg	Water/kg
12	Fine sandstone	837	3.1	126	0.9	2.2		2.77
11	Siltstone	728	12.2	122.9	2.8	10.8		11
10	Siltstone	728	1.5	110.7	0.3	1.4		1.39
9	Siltstone	728	6.9	109.2	1.5	6.3		6.21
8	Coarse Grained Sandstone	973	17.1	102.3	10.5	4.9		15.4
7	No.11 coal		5.1	85.2	1	5	19.8	4.6
6	Fine Grained Sandstone	837	25.8	80.1	8.1	18		23.4
5	Siltstone	728	7.2	54.3	1.5	6.3		6.3
4	No.12 coal		19.9	47.1	3.9	19.5	78	18
3	Siltstone	728	6.6	27.2	1.5	6		6
2	Fine Grained Sandstone	837	5.2	20.6	1.6	3.7		4.7
1	Siltstone	728	15.4	15.4	3.6	13.8		13.8

The thickness of the top coal is greater than 3.4m, it is more stable based on the results in section 2. So, the top coal thicknesses of 3.0m, 3.5m, and 4m are designed in the experiment, and the other parameters of the open-off cut are consistent with the in-situ. The die is embedded to the physical model forming the open-off cut during the model-built process. More detailed parameters about the open-off cut are shown in Table 2. The upper gob is formed by mining the upper 12203 working face. Then, with the embedded mold extracted six times from the physical model, the excavated process of the open-off cut with different thickness of top coal is simulated.

Table 2 The designed parameters of the open-off cuts in the similarity model

Open-off cut	Top coal thickness in-situ /m	Top coal thickness in the model /mm	Excavation depth of the floor in the model /mm
No.1	3.0	60	18.8
No.2	3.5	70	28.8
No.3	4.0	80	38.8

### 3.2 Model monitoring program

To monitor the deformation characteristics of the surrounding rock of the open-off cut with different top coal thicknesses, the method of distributed optical fibre sensing (DOFS) based on BOTDA were utilized to monitor the internal deformation of the surrounding rock in the physical model experiment. An optical fibre with 2 mm diameter, named H<sub>1</sub>, was arranged horizontally in the top coal of the open-off cut in this experiment. Three vertical optical fibres same as horizontal fibre H<sub>1</sub>, named V<sub>1</sub>, V<sub>2</sub>, and V<sub>3</sub>, were arranged at the top coal centre of the open-off cut 1-3. The layout details of the test system can be found in Figure 7. The NBX-6055 optical nanometre with a spatial resolution of 5 cm and a sampling interval of 1 cm, an optical fibre signal demodulation equipment, was utilized in the experiment.

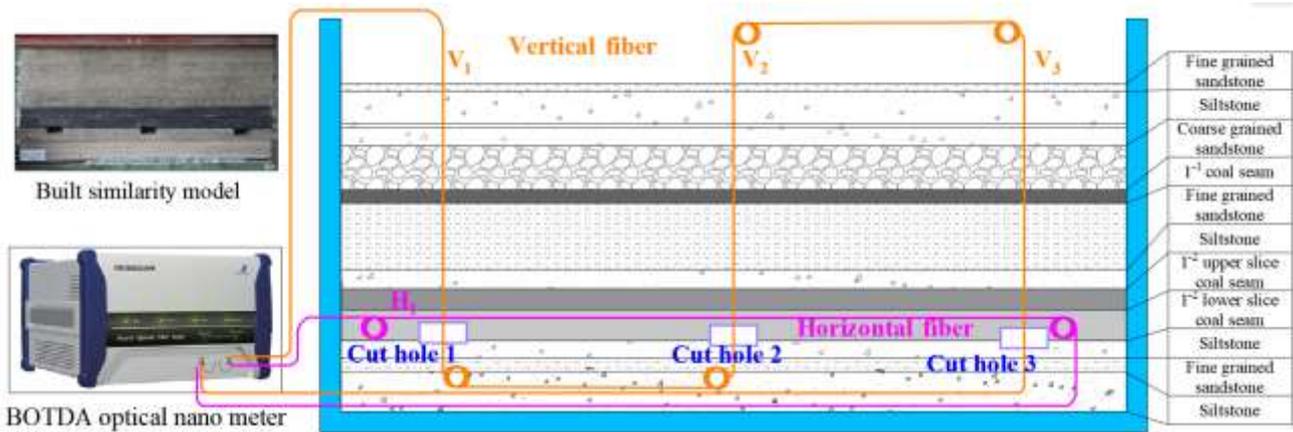
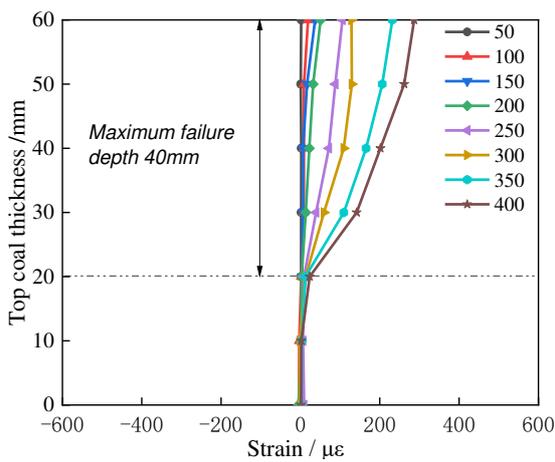


Fig. 7 Schematic diagram of open-off cut layout

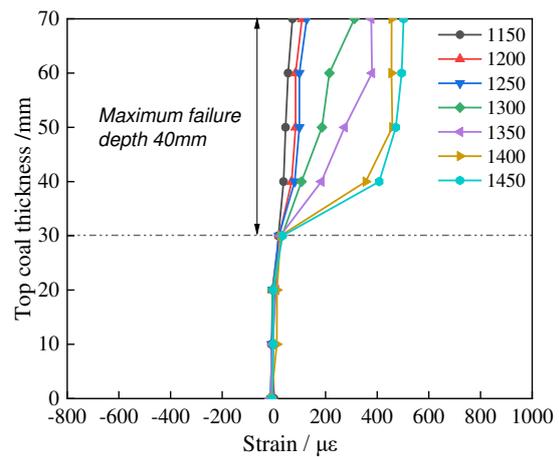
## 4 Results and discussion

### 4.1 The failure depth of top coal in the upper slice working face mining

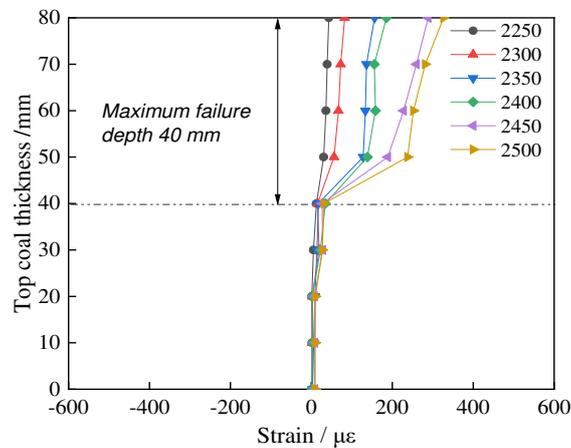
The data of vertical fibre  $V_1$  when the working face is advanced from 50mm to 400mm, the data of vertical fibre  $V_2$  when the working face is advanced from 1150mm to 1450mm, and the data of vertical fibre  $V_3$  when the working face is advanced from 2250mm to 2500mm are extracted respectively, as shown in Figure 8.



(a) Damage depth of top coal in open-off cut 1



(b) Damage depth of top coal in open-off cut 1



(c) Damage depth of top coal in open-off cut 1

Fig. 8 Damage depth of top coal in mining cut of upper layered working face

As is shown in Figure 8, a gob is formed above the top coal of cut 1-3 with the mining of the upper layered working face. The stress is reduced with the top coal produced expanded deformation to the gob. The vertical optical fibre is pulled by in the expansion process of the top coal, resulting in positive strain. The damage extent and depth of top coal can be characterized by the magnitude and range of fibre strain. The damage depth of top coal gradually increases in the working face passing through the top coal position of open-off cuts 1-3. After the top coal completely enters the gob, the maximum damage depth is up to 40mm.

#### 4.2 Vertical deformation characteristics of top coal

The deformation characteristics of the top coal measured by the vertical optical fibre during the cutting excavation are shown in Figure 9. During excavation, the vertical deformation of the open-off cuts 1 and 2 top coal can be divided into the mining influence area and the excavation affected area. There is a stable area with a thickness of about 0.5m in the middle of the top coal in open-off cut 3. The top coal deformation area can be divided into the mining-affected area, stable area, and excavation-affected area.

The top coal thickness of open-off cut 1 is the smallest in the experiment. Affected by the excavation disturbance, the deformation of top coal gradually increases with the increase of the excavation times within the range of the top coal thickness. The deformation in the excavation-affected area is greater than that in the mining-affected area, and the coal below the mining-affected area is greatly affected by the excavation, and the subsidence increases obviously. As shown in Figure 9, there is a composite disturbance affected area in the middle of the top coal. The maximum deformation in the mining-affected area reaches  $548 \mu\epsilon$  after excavation, and the excavation affected area reaches  $822 \mu\epsilon$ . The subsidence trend of top coal is obvious, and its stability is poor.

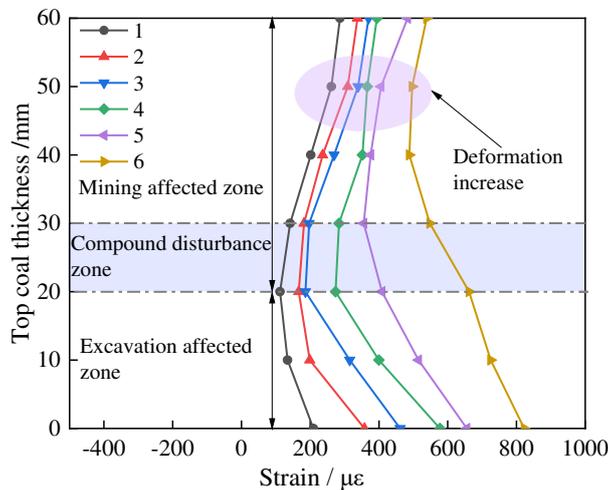
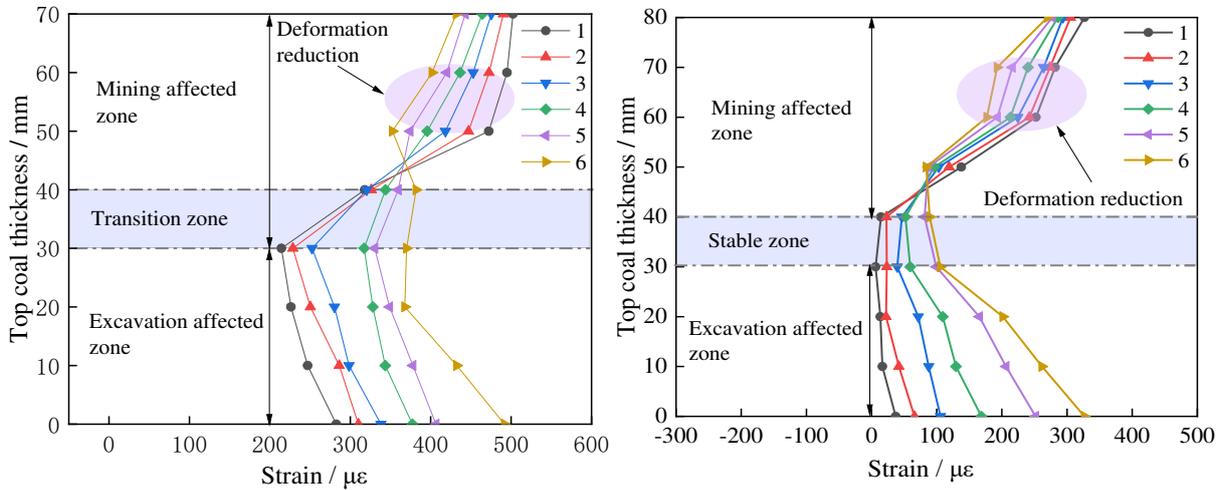


Fig. 9 Deformation characteristics of top coal during excavation of open-off cut 1

As shown in Figures 10(a) and (b), during the excavation of open-off cuts 2 and 3, the coal body above the mining-affected area is progressively compacted by the gangue in the upper gob, and the deformation of the coal body shows a decreasing trend. It implies that the mining-affected area and the excavation-affected area of open-off cuts 2 and 3 are not interplayed, and there are some stable coal bodies in the middle of the top coal.

As shown in Figure 10 (a), under the excavation effect, the deformation between 30mm and 40mm in the middle top coal of open-off cut 2 initially reduces and then rises. The zone is the transition area between mining and excavation influence. After the excavation is completed, the maximum deformation of top coal in the mining-affected area reaches 381  $\mu\epsilon$ , and the excavation affected area reaches 491  $\mu\epsilon$ . The subsidence trend of top coal is obvious, and it is comparatively stable.



(a) Deformation characteristics of top coal in open-off cut 2 (b) Deformation characteristics of top coal in open-off cut 3

Fig. 10 Deformation characteristics of top coal during excavation of open-off cuts 2 and 3

During the excavation, the deformation is the same between 30-40mm in the middle of the top coal of open-off cut 3. It indicates that there is a stable area with a thickness of about 10mm in the middle of the top coal, which is relatively stable under the influence of mining and excavation. As is illustrated in Figure 10 (b). The deformation in the mining-affected area of top coal is a relative decrease, under the influence the gangue gradually compacted in the gob. With the increase in excavation times, the deformation of top coal in the excavation affected area gradually increases. The maximum deformation of top coal in the mining-affected area reaches 90  $\mu\epsilon$  after the excavation is completed, and the excavation affected area reaches 326  $\mu\epsilon$ . The top coal deformation of open-off cut 3 in the excavation-affected area is only 39.6% and 66.3% of that in cut 1 and cut 2. The subsidence of top coal is small and the roof is more stable.

### 4.3 Horizontal deformation characteristics of top coal

During the excavation of open-off cut1-3, the horizontal deformation of the top coal with the optical fiber monitored was take the center of the width of open-off cut top coal as 0 point, as shown in Figure 11. It can be seen that the deformation of top coal presents a "W" type distribution. According to the deformation characteristics of positive tension and negative pressure of optical fiber sensing, it shows that the middle part of the top coal has obvious subsidence under the influence of self-weight and the load of the overlying gob. With the continuous excavation of the open-off cut, the subsidence within  $\pm 50$ mm of the top coal center of the open-off cuts 1-3 are significantly greater than that on both sides, showing the zoning characteristics of large deformation in the middle and small deformation on both sides. It shows that when the open-off cut width is 9.96m, the roof deformation is large within 5m of the open-off cut center. If the support is not timely, the top coal has a large risk of falling. In this paper, the area within  $\pm 50$ mm of the top coal center is divided into a roof fall hazard area.

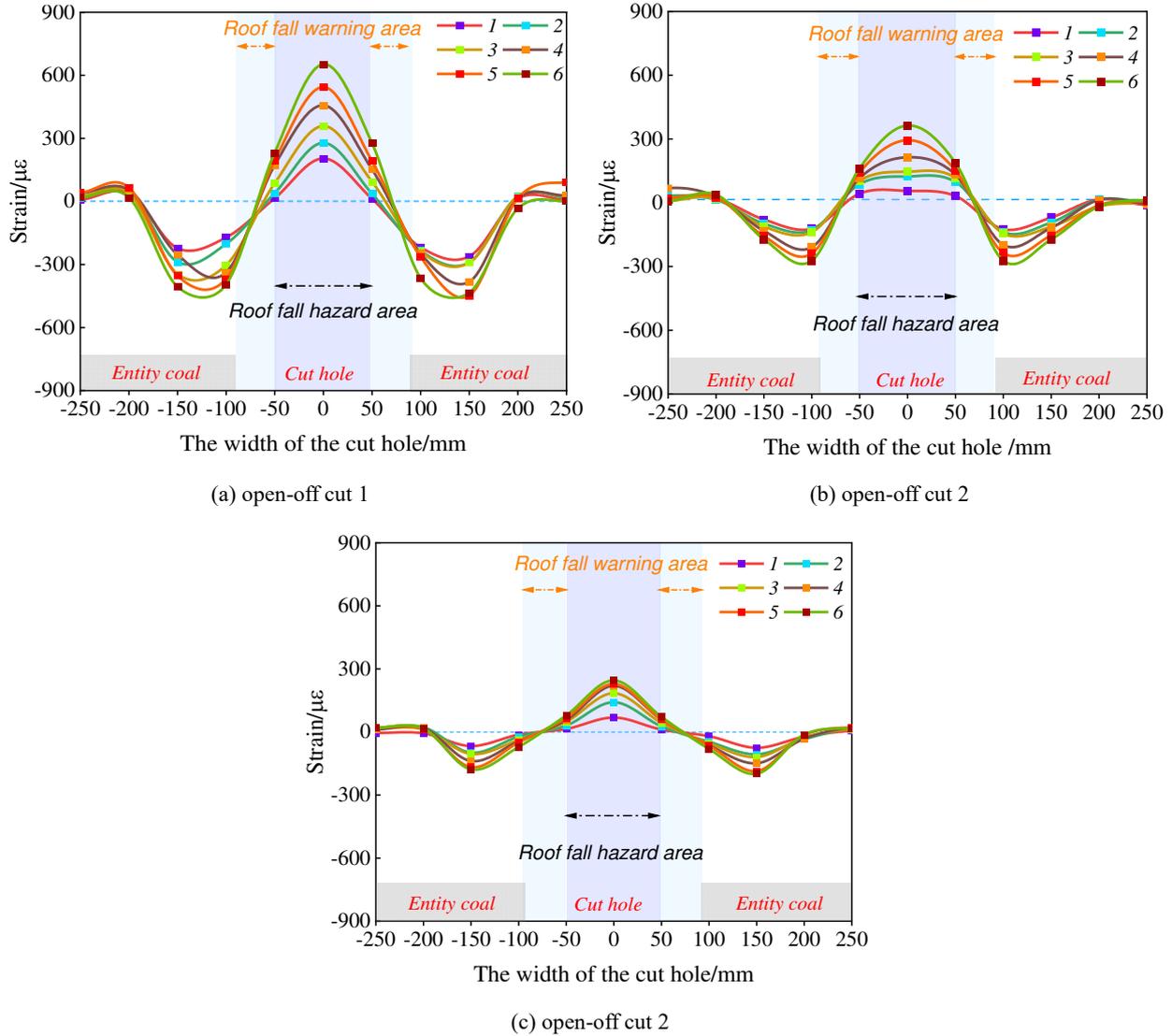


Fig. 11 Deformation of open-off cut roof detected by distributed optical fiber

Within the range of  $\pm 50$ - $100$ mm on both sides of the open-off cuts 1-3, the horizontal deformation results gradually change from positive strain to negative strain, indicating that the top coal subsidence gradually decreases near the two sides of the open-off cut. With the increase of the excavation distance of the open-off cut, the subsidence of the top coal around the open-off cuts 1-3 also gradually increases, but the peak deformation is only 7%-37% of the open-off cut center, and the stability is high. Therefore, within 2.5m of the two sides of the open-off cut, the probability of top coal fall caving is small, and this area can be divided into a top coal caving early warning area.

#### 4.4 Deformation laws of top coal horizontal zoning

The deformation characteristics of the roof fall hazard area are shown in Figure 12 during the excavation of open-off cuts 1-3. Compared to the optical fiber test results of the open-off cuts 1-3, the top coal center subsidence in the roof fall hazard area of the cut 1 is significantly greater than that of the open-off cuts 2 and 3 at each excavation stage. The roof fall hazard area deformation of the open-off cut 1 up to  $652 \mu\epsilon$  after the open-off cut is through. The deformation of the cut eye 2 is  $363 \mu\epsilon$ . The deformation amount is about 56% of that of open-off cut 1. The deformation of open-off cut 3 is the

smallest, and the subsidence of top coal after open-off cut through is only 228  $\mu\epsilon$ , it is about 35% of the open-off cut 1.

As shown in Figure 12, it is found that the subsidence of the roof fall hazard area of the open-off cuts increases exponentially when the thickness of the top coal is 3m. When the thickness of top coal is 3.5m, the deformation in the roof fall hazard area in the cut is approximately linear. When the thickness of the top coal is 4m, the deformation in the dangerous area of the top coal caving in the open-off cut increases logarithmically. It shows that when the open-off cut width is certain, the top coal thickness of 12203 working face is set as 3m, the stability of the top coal is poor, the subsidence of roof fall hazard area increases exponentially, the deformation of the top coal is large, and the maintenance of the cutting is difficult. The thickness of the top coal is set as 3.5m, the stability of the top coal is moderate, the subsidence in the roof fall hazard area increases linearly, and the deformation of the top coal is in the middle. When the thickness of the top coal is set as 4m, the stability of the top coal is higher, and the subsidence in the roof fall hazard area increases in an approximate logarithmic law. The deformation of the top coal changes little within a certain time after the open-off cut through.

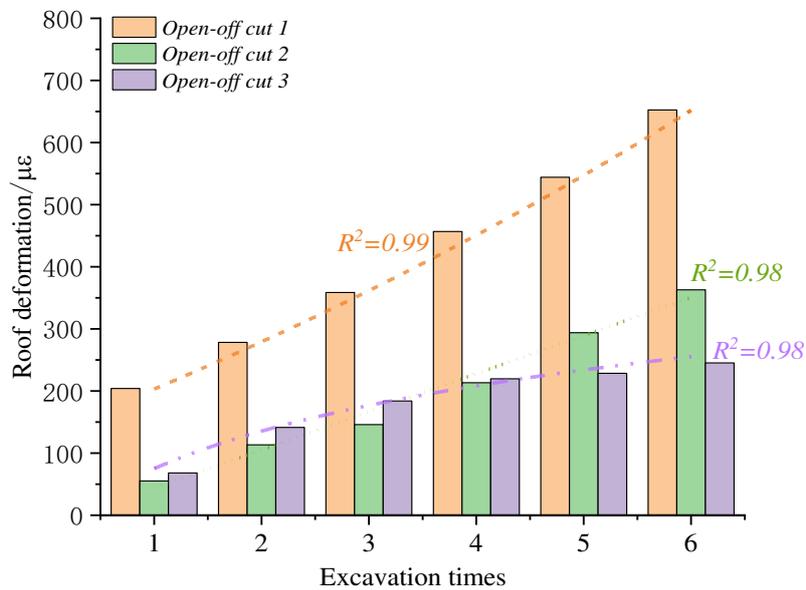
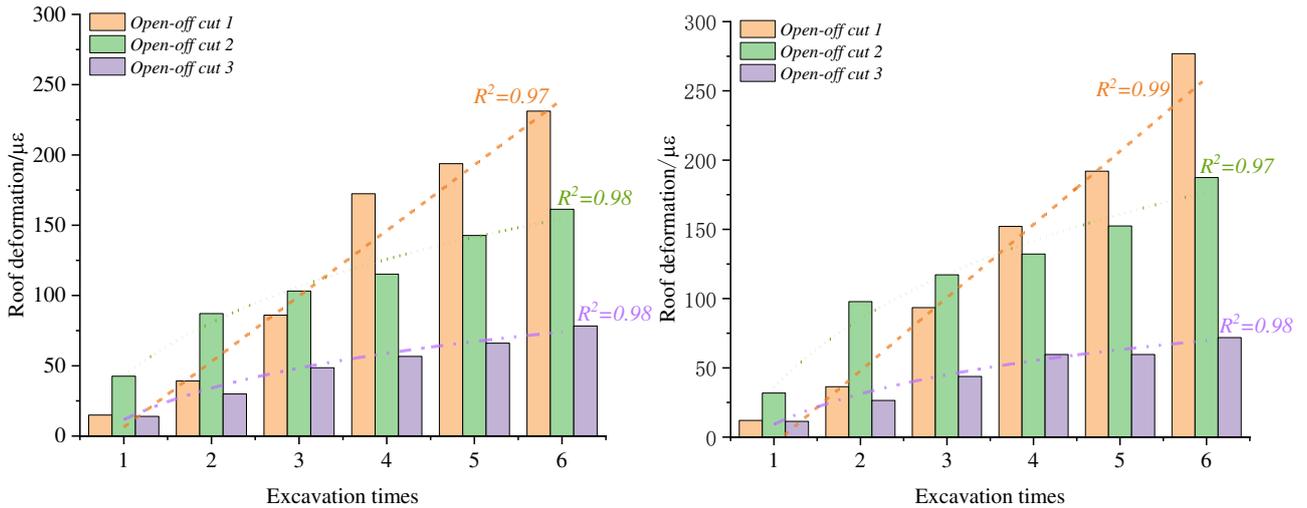


Fig. 12 The deformation law of roof fall hazard area

The deformation law of the roof fall warning area of the open-off cut with different top coal thickness is shown in figure 13. The deformation characteristics of the roof fall warning area on the left side of the open-off cut 1-3 are shown in the Figure 13 (a), and the results of right side are shown in Figure 13 (b). It can be found that with the increase of excavation times, the subsidence of the roof fall warning area on the left and right sides of the open-off cut 1 increases approximately linearly, and the deformation on the left side area of the open-off cut 1 reaches 231  $\mu\epsilon$  when the cut through, and the right area falling reaches 278  $\mu\epsilon$ . The subsidence of the roof fall warning area at the left and right sides of open-off cuts 2 and 3 rises logarithmically, and the growth rate of the top coal subsidence steadily declines after the third excavation. The subsidence of the area on the left side of open-off cut 2 after through is 161  $\mu\epsilon$ , 187  $\mu\epsilon$  on the right. The area on the left side of open-off cut 3 is 79  $\mu\epsilon$ , 72  $\mu\epsilon$  on the right. The roof fall warning area of open-off cut 2 and 3 is significantly smaller than that of open-off cut 1.



(a) The deformation law at the 50mm to left of top coal (b) The deformation law at the 50mm to right of top coal

Fig. 13 The deformation law of roof fall warning area

The above analysis shows that when the thickness of the top coal of the open-off cut is 3m, the subsidence of the roof fall warning area increases linearly with the excavation of the open-off cut. The stability of the top coal is poor, and the probability of roof fall danger within a certain time after the cut is through is large. When the thickness is 3.5m and 4m, the subsidence of the top coal caving warning area increases logarithmically with the open-off cut excavation. The deformation in the top coal caving warning area obviously slows down during the fourth to sixth excavation, and the top coal stability is good.

By comparing figures 13(a) and (b), under different top coal thicknesses, along the open-off cut width direction, the deformation of roof fall hazard area during the open-off cut excavation is significantly greater than that of roof fall warning area. The thickness of the top coal is 3m, the deformation law of the top coal changes from exponential to linear deformation from roof fall hazard area in the center to roof fall warning area on both sides. The stability of the top coal is poor and the risk of roof fall is high. When the thickness of the top coal is 3.5m, the deformation law of the top coal changes from linear to logarithmic deformation from roof fall hazard area in the center of the top coal to the roof fall warning area on both sides. The top coal shows a certain self-stability, and the stability is good. When the thickness of the top coal is 4 m, within the width of the open-off cut, whether it is in the roof fall hazard area or the warning area, the subsidence law of the top coal is a logarithmic deformation law. The top coal shows a good self-stability ability, and the stability is higher.

## 5 Discussions

### 5.1 Determination of reasonable top coal thickness

According to the experimental results, the thickness of the top coal in the large section open-off cut under the gob is increased from 3.0m to 4.0m, and the subsidence deformation law in roof fall hazard area changes from the exponential to the linear, and finally turns to the logarithmic subsidence law. It will take some time for shunting between the continuous excavator and the anchor bolt machine after the excavation of the open-off cut in-situ. There is an empty roof period in a certain range in front of the open-off cut. When the thickness of the top coal is 3m, the subsidence amount and speed of the top coal are large, which is not conducive to on-site safety. When the thickness of the top coal is 4m,

the roof fall hazard area sinks in a logarithmic relationship. The subsidence of the top coal is small, which has a good self stabilization ability. The strong support method is adopted on site, and the stability of the open-off cut is the highest. However, there are shortcomings of large undercover depth and waste of coal resources. When the thickness of top coal is 3.5m, the roof fall hazard area sinks with linear deformation law, and the stability of top coal can be guaranteed after strong support. It can not only reduce the undercover amount, but also improve the coal recovery rate. To sum up, when the thickness of top coal is 3.5m, it is not only conducive to the stability of top coal, but also conducive to on-site construction and improves the resource recovery rate.

### 5.2 Field observation on stability of top coal in the 12203 open-off cut

The reserved thickness of top coal is 3.5m on site. The deformation of the top coal in the 12203 open-off cut is observed through the borehole peep and the roof separation instrument. As shown in Figure 14, there are some small horizontal fracture near 0.9m of the top coal. There are some coal chips at 1.75m and 2.56m. With small fracture development, the top coal at 3.43m is relatively broken due to the influence of the overlying gob. The monitoring results of the roof separation instrument are shown in Figure 15. The maximum separation inside the top coal is 6mm after 70 days of monitoring. The results of comprehensive borehole peeping and roof separation monitoring show that the top coal is relatively stable when the top coal thickness is 3.5m under the condition of support.

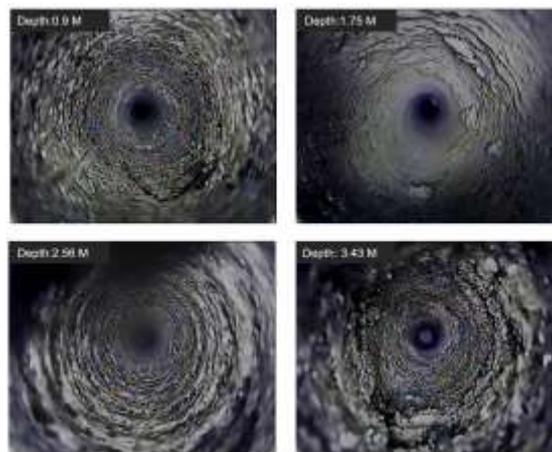


Fig. 14 Top coal integrity on 12203 open-off cut

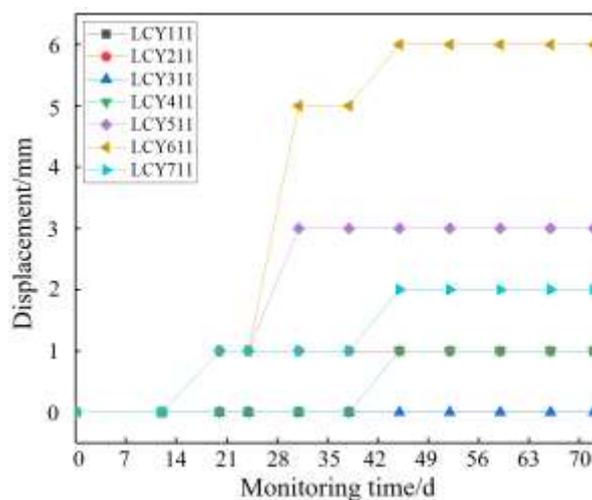


Fig.15 Observation results of roof layer separation instrument

## 6 Conclusions

(1) Based on the theoretical calculation results, the thickness of top coal in large cross-section cut of 12203 working face in Huojitu minefield is greater than 3.4m, there is no tension crack, and the thickness is greater than 1.2m, the top coal does not slip along the through crack.

(2) The top coal deformation of the open-off cut is affected by both mining and excavation disturbance in the vertical direction, which can be divided into mining disturbance area and excavation disturbance area. The thickness of top coal is 3m, there is a complex disturbance zone in the middle of the top coal, and the stability is poor. The thickness is 3.5m, there is a mining and excavation disturbance transition zone in the middle of the top coal. The thickness is 4m, there is a certain thickness of stable zone in the middle of the top coal, and the stability is good.

(3) The top coal deformation of the open-off cut in the span direction can be divided into roof fall hazard area and warning area from the center of the open-off cut to both sides. During the open-off cut excavation, the deformation law of the top coal in the roof fall hazard area changes from exponential linear logarithmic, and the deformation of the top coal in the roof fall warning area changes from linear to logarithmic. The thickness of the top coal increases and the subsidence in the two areas decreases.

(4) The thickness of the top coal of the cut is 3.5m, the top coal in the roof fall hazard area increases linearly with the increase of excavation times, and the stability is moderate. It is comprehensively determined that 3.5m top coal is reserved on site. After support, the top coal has good integrity, and the maximum layer separation is 6mm, which can meet the production requirements.

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### **Data availability**

The data used to support the findings of this research are included within the paper.

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**Author contributions**

Chai, J. conceived the study; Liu, Y.L. were the principal investigators; Gao, S.G. and Zhang, D. D. directed the overall study design; Yang, J.F. and Du, W.G. performed the experiments; Ma, C.Y. and Han, Z.C. analyzed the data. All authors discussed and interpreted the results.

**Competing interests**

The authors declare no competing interests.

**Additional information**

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