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Article

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Mechanism and control of strong ground pressure in shallow buried ultra-large mining height working face with directly overlying double key strata

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Abstract

When mining in shallow buried ultra-large mining height working faces with directly overlying double key strata, the working face is often accompanied by periodic strong dynamic load weighting. During weighting periods, the support has large convergence and high safety valve opening rate, which brings serious hidden dangers to safe and efficient mine production. Taking the 122104 fully mechanized working face with 10 m ultra-large mining height in Caojiatan coal mine of Yushen Mining Area as the engineering background, field observation and physical similarity simulation were adopted to study the overburden structure characteristics of shallow buried ultra-large mining height mining with directly overlying double key strata. A mechanical model of roof control was established, and a theoretical calculation method of support working resistance for ultra-large mining height working face was proposed. The research results show that: (1) Physical simulation shows that when mining in shallow buried ultra-large mining height working face with directly overlying double key strata, the lower key stratum has a large rotation angle, forming a long cantilever structure after initial fracture, and a low-level stepped rock beam structure during periodic fracture. It controls the movement of overlying strata within 22 m, which is the main reason for the small-period weighting of the working face. After the upper key stratum fractures, it forms a voussoir beam structure. Its periodic rotation and subsidence may force the lower key stratum to fracture in advance, and drive the load of the overlying non-key strata to be transmitted to the working face, causing large-period weighting. (2) Mechanical analysis shows that the setting load of supports in the initial mining stage should ensure that the fractured blocks of the lower key stratum do not undergo sliding instability. In the small-period weighting stage dominated by the first key stratum, the working resistance should include two parts: the weight of strata in the caving zone and the balance force used to balance the hinged structure of the second key stratum. During large-period weighting, the first key stratum, the second key stratum and the overlying strata groups controlled by them move synchronously, resulting in that the existing supports of the working face cannot meet the bearing demand in the large-period weighting stage. (3) Physical experiments of roof pre-splitting show that after implementing hard roof pre-splitting, the initial and periodic fracture intervals of the first key stratum are reduced by 57.98% and 52.97% respectively, and those of the second key stratum are reduced by 56.6% and 60.78% respectively. The maximum stress concentration coefficient of the working face is reduced by 19.86%. (4) Engineering verification shows that after hard roof pre-splitting, the periodic weighting interval ranges from 9.71 m to 24.19 m with an average of 16.7 m, which is 37.17% smaller than the physical simulation results, and the field ground pressure behavior is stable.

Keywords: Extra-thick coal seam; Ultra-large mining height; Near-field key strata; Overburden structure; Similarity simulation; Working resistance.

1 Introduction

Ultra-large mining height fully mechanized mining technology has become the main

development direction of extra-thick coal seam mining in China due to its advantages of high coal recovery rate and low roadway driving rate[1,2]. However, with the increase of mining height, the height of the overburden caving zone increases accordingly[3]. The middle and low strata that can form a stable voussoir beam structure by extrusion and occlusion with adjacent rock blocks in conventional mining height working faces will also lack sufficient horizontal extrusion force due to the large rotation angle of blocks, which is prone to sliding instability[4]. This leads to insufficient stability of the formed short voussoir beam or stepped rock beam structure, causing the overburden load to be transmitted to the working face supports in a wide range, resulting in strong ground pressure behaviors such as large support convergence and high safety valve opening rate[5,6]. The above problems have become basic problems affecting the popularization and application of large mining height fully mechanized mining technology. Therefore, it is necessary to conduct in-depth research on the overburden structure characteristics and weighting mechanism of large mining height fully mechanized mining.

The ground pressure behavior of the working face originates from overburden fracture and structural adjustment movement[7]. As the key stratum that controls overburden movement, its fracture and subsequent formed overburden structure directly determine the ground pressure behavior of the working face[8]. In terms of extra-thick coal seam mining and ground pressure control, due to the large mining space of the coal seam, the overburden disturbance range is wide and the affected horizon is high[9]. Such complex ground pressure phenomena are often difficult to be fully explained only by traditional ground pressure theories. For example, even if the key ground pressure horizons are accurately identified and controlled through classical theories, the occurrence of strong ground pressure, support safety valve opening and even support crushing accidents still occur frequently[10-12]. In response to this problem, domestic researchers have conducted in-depth discussions on the overburden structure and ground pressure mechanism of extra-thick coal seams, and generally believe that the special overburden structure characteristics and the formation of large-space stope are the main reasons for abnormal ground pressure performance[13,14]. Based on this, by analyzing the migration characteristics of high-level rocks, a series of mechanical models of overburden structure were established. The ground pressure mechanism of large-space stope was explored from different perspectives such as "short cantilever beam - hinged rock beam structure"[15,16], "cantilever structure and voussoir beam structure"[17-19], "near and far field", "large space"[20,21], "upper voussoir beam - lower inverted stepped combined cantilever beam"[22,23], "combined cantilever beam - elastic long beam"[24]. At the same time, relevant scholars have conducted detailed studies on the fracture mechanism of high-level thick hard strata and the movement law of blocks after fracture[25-28], aiming to reveal the ground pressure change law before and after stope roof fracture[29-31].

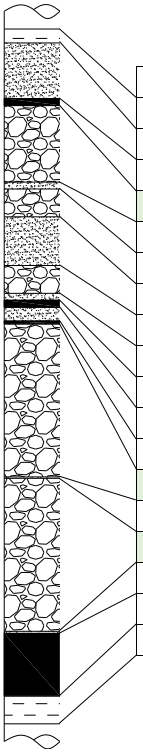
In terms of calculating the support working resistance of large mining height extra-thick coal seam working faces, Zhang et al[32] established UDEC models of different horizons of key strata, studied the influence of key stratum position on support working resistance during large mining height fully mechanized top-coal caving mining, and derived the estimation formula of maximum support working resistance. Li[33] discovered and defined 6 movement types of the first key stratum in large mining height fully mechanized working face, established the bearing load calculation model of each movement type, and obtained the support working resistance formula of each movement type. Wu[34] analyzed the "combined cantilever beam - non-hinged roof - hinged roof" structural form of roof in large mining height working face and the calculation method of reasonable support resistance. Huang et al[35,36s] established a double key stratum structure of shallow buried coal seam large mining height working face, and obtained the calculation method of reasonable support working resistance.

As mentioned above, most existing studies on strong ground pressure behavior of shallow buried

coal seam large mining height mining in Yushen Mining Area focus on the influence of high-level main roof strata activity, and there are few studies on the structural characteristics and activity law of low-level double main roof strata. In the mining practice of extra-thick coal seam of Yan'an Formation in Middle Jurassic of Yushen Mining Area, dynamic disasters occur frequently in working faces and roadways. It is necessary to more comprehensively reveal the structural characteristics and evolution law of strata at different horizons in the stope, propose new theories and determination methods of support working resistance adapted to ultra-large mining height fully mechanized top-coal caving mining of extra-thick coal seams, so as to provide theoretical basis for ensuring the safe mining of ultra-large mining height of extra-thick coal seams. Therefore, taking the mining conditions of directly overlying double key strata in ultra-large mining height working face of Caojiatan coal mine in Yushen Mining Area as an example, similarity simulation tests and theoretical analysis were used to study the structural characteristics and evolution law of overlying strata in fully mechanized top-coal caving stope of extra-thick coal seam with ultra-large mining height, reveal the influence of near-field key stratum overburden structure on hydraulic support load of working face, and quantify the regulation effect of roof pre-splitting on key stratum fracture parameters and working face ground pressure. This research has certain practical significance for the safe, efficient and sustainable mining of fully mechanized top-coal caving stope in extra-thick coal seam with ultra-large mining height.

2 Engineering background

The 122104 fully mechanized working face of Caojiatan coal mine mines the 2-2 coal seam. The working face adopts 10 m ultra-large mining height fully mechanized mining technology, with a dip length of 300 m and a strike length of 5977 m. The north side of the working face is unmined solid coal, and the south side is the goaf of 122106 working face. The coal seam has a buried depth of 363 m, an average thickness of 10.5 m, a coal seam dip angle of 0-6°, an average mineable thickness of 10.5 m. The borehole column of overburden in the working face is shown in Figure 1.



Lithology	Thickness, m	Depth, m
Sandy mudstone	2	276.4
Siltstone	8	278.4
Coal seam	1	286.4
Fine sandstone	11	287.4
Siltstone	1	298.4
Fine sandstone	4	299.4
Siltstone	7	303.4
Fine sandstone	4	310.4
Siltstone	1	314.4
Coal seam	1	315.4
Siltstone	2	316.4
Coal seam	0.4	318.4
Medium-grained sandstone	22	318.8
Mudstone	0.2	340.8
Medium-grained sandstone	22	341
Siltstone	0.3	363
2^{-2}Coal seam	9	363.3
Sandy mudstone	4	372.3

Figure 1 Stratigraphic column.

The working face adopts 10 m ultra-large mining height fully mechanized mining technology,

and the average advancing speed during normal mining is about 12.6 m/d. A total of 129 hydraulic supports are arranged, among which the basic support is ZY29000/45/100D hydraulic support, with a maximum support height of 10 m, a rated working resistance of 29,000 kN, a rated setting load of 22,368 kN, a support center distance of 2400 mm, and a support strength of 1.88-1.95 MPa.

3 Fracture and movement characteristics of directly overlying double key strata

3.1 Physical similarity simulation experiment

To grasp the dynamic migration law of near-field key stratum overburden and ground pressure behavior law under the condition of directly overlying double key strata in ultra-large mining height working face, physical similarity simulation research was carried out. The physical similarity simulation experiment adopts a 2 m plane model with a similarity ratio of 1:100. Excluding the reserved boundary of each frame, the simulated advancing length of the working face is 190 m, and the simulated mining height is 10 m. The geometric similarity ratio is 1:100; the stress similarity ratio is set accordingly. The similar materials are whiting, gypsum and river sand, and the proportions are shown in Table 1. The upper part of the model is weighted with iron bricks. The model is excavated from right to left, with 12.5 cm per excavation. 53 groups of stress sensors are arranged at the bottom of the model, and two groups of displacement survey lines are set at the top positions of two layers of 22 m thick medium-grained sandstone. The stress and displacement change laws are collected respectively during excavation. The experimental model is shown in Figure 2.

Table 1 Proportion table of physical similarity model

Rock Strata	Similar material proportion						
	Thickness/m	Proportion	Sand/kg	Gypsum/kg	Whiting/kg	Coal ash/kg	Total weight/kg
Sandy mudstone	2	846	10.8	0.5	0.8	0	12.2
Siltstone	8	728	42.6	1.2	4.9	0	48.7
Coal seam	1	928	2.9	0.12	0.5	2.6	6.1
Fine sandstone	11	746	58.6	3.3	5.0	0	66.9
Siltstone	1	728	5.3	0.2	0.6	0	6.1
Fine sandstone	4	746	21.3	1.2	1.8	0	24.4
Siltstone	7	728	37.3	1.1	4.3	0	42.6
Fine sandstone	4	746	21.3	1.2	1.8	0	24.4
Siltstone	1	728	5.3	0.2	0.6	0	6.1
Coal seam	1	928	2.9	0.1	0.5	2.6	6.1
Siltstone	2	728	10.7	0.3	1.2	0	12.2
Coal seam	0.4	928	1.2	0.1	0.2	1.0	2.4
Medium-grained sandstone	22	737	234.4	10.0	23.4	0	267.9
Mudstone	0.2	84.6	1.08	0.05	0.08	0	1.22
Medium-grained sandstone	22	737	234.4	10.0	23.4	0	267.9
Siltstone	0.3	728	1.6	0.1	0.2	0	1.8
2^{-2}Coal seam	9	928	27..3	1.1	4.4	22	54.8

Sandy mudstone	4	846	21.6	1.1	1.6	0	24.4

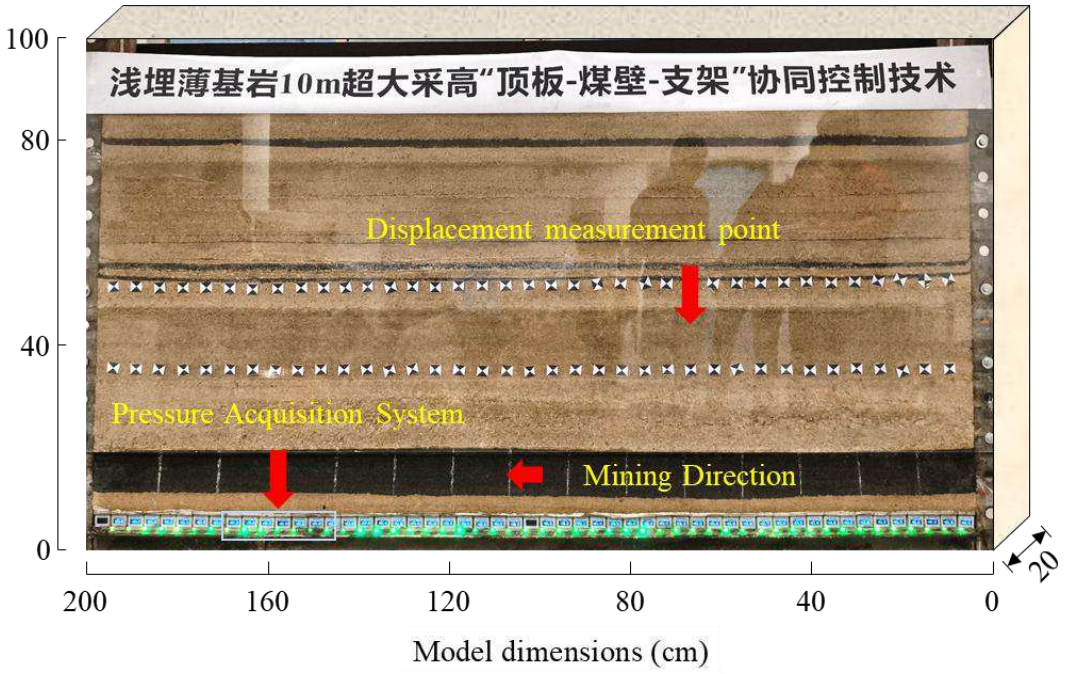


Figure 2 Overall view of the physical similarity model.

3.2 Fracture and movement characteristics of overburden

(1) Long cantilever structure of initial fracture of lower strata

When the working face advances to 94.6 m, tensile cracks occur on the upper surface of the beam end of the first key stratum (Figure 3(a)), and bed separation occurs; when advancing to 119 m, initial fracture occurs, the fracture line is located in the goaf, and the overburden activity range is 0~22 m (load layer). After the rock stratum fractures, the fractured rock block does not occlude with adjacent rock blocks to form a hinged structure, but cuts off behind the support in the form of a long cantilever structure, while the rock block to be fractured continues to be exposed (Figure 3(b)).

(2) Short cantilever structure of periodic fracture of lower strata

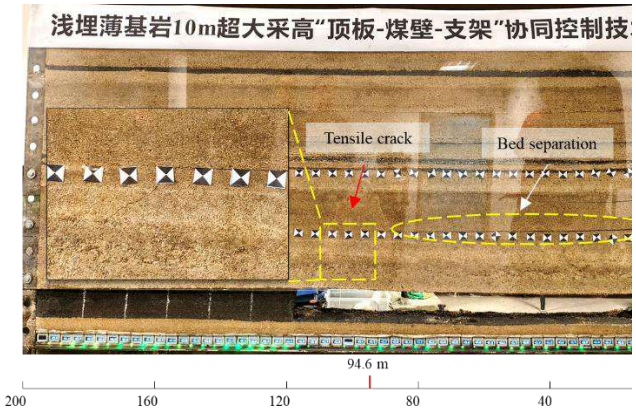
With the continuous advancement of the working face, the exposed length of the cantilever structure increases (Figure 3(c)). When advancing to 148.3 m and the cantilever length reaches 26.58 m (Figure 3(d)), the rock stratum enters periodic fracture.

(3) Sliding instability of cantilever structure of lower strata

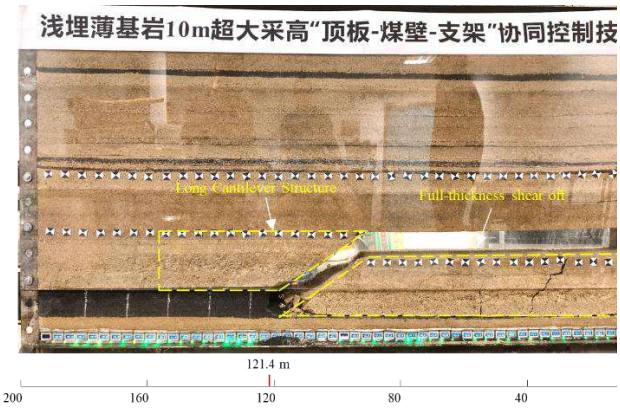
Similar simulation experiments show that during mining in ultra-large mining height working face, the lower key stratum structure will undergo an evolution process of "cantilever structure - cantilever structure fracture - new cantilever structure - periodic fracture of cantilever structure" during initial and periodic fracture. In the above two stages, the fractured rock blocks all undergo sliding instability due to large rotation angle and lack of sufficient horizontal extrusion force.

(4) Rotation and subsidence of upper voussoir beam structure

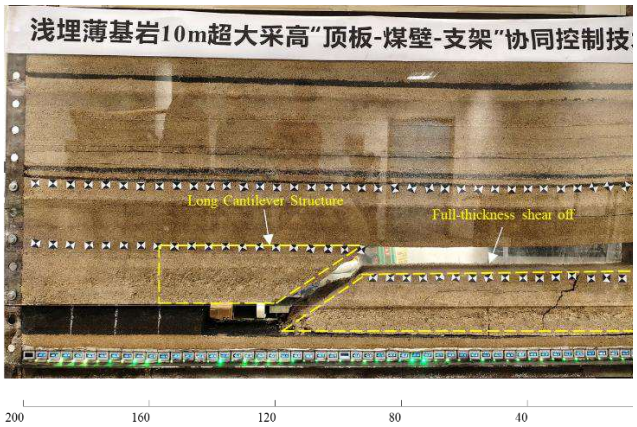
When the working face advances to 148.3 m and the lower key stratum undergoes the first periodic fracture, it triggers the fracture of the upper key stratum, leading to instantaneous fracture and subsidence of strata in the 20~80 m range controlled by it, and causing severe weighting. After fracture, the second key stratum rotates and subsides, and finally forms a voussoir beam structure (Figure 3(d)). In the weighting stage dominated by the second key stratum, its fracture can cause synchronous movement of a wide range of overburden strata, and it belongs to the main control key stratum.



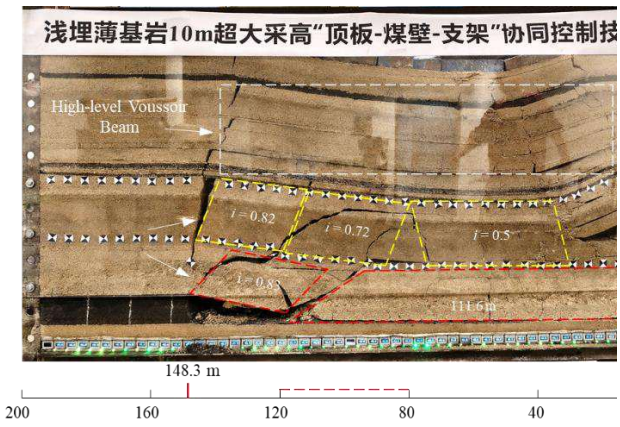
（a）Advancing to 94.6 m, long cantilever structure in the initial mining stage



（b）Advancing to 121.4 m, sliding instability of the long cantilever structure



（c）Advancing to 137.5 m, the lower cantilever structure remains exposed



（d）Advancing to 148.3 m, the upper key stratum forces the lower key stratum to fracture in advance

Figure 3 Long cantilever structure and sliding instability of the lower key stratum during initial fracture.

3.3 Stage growth of stress and periodic adjustment characteristics of overburden structure

During the advancement of the working face, the stress of the coal seam floor is collected in real time, and the pressure distribution curves under different advancing steps are obtained (Figure 4). It can be seen from Figure 4 that with the advancement of the working face, the evolution of the advanced abutment pressure of the working face has the characteristics of stage growth with large and small periods, and this stress evolution characteristic is closely related to structural adjustment.

(1) Initial mining stage

When the working face advances from the open-off cut to 100 m, the advanced abutment pressure shows a monotonically increasing trend, increasing from 2.24 MPa to 32.67 MPa. This stage corresponds to the overburden structure of long cantilever structure.

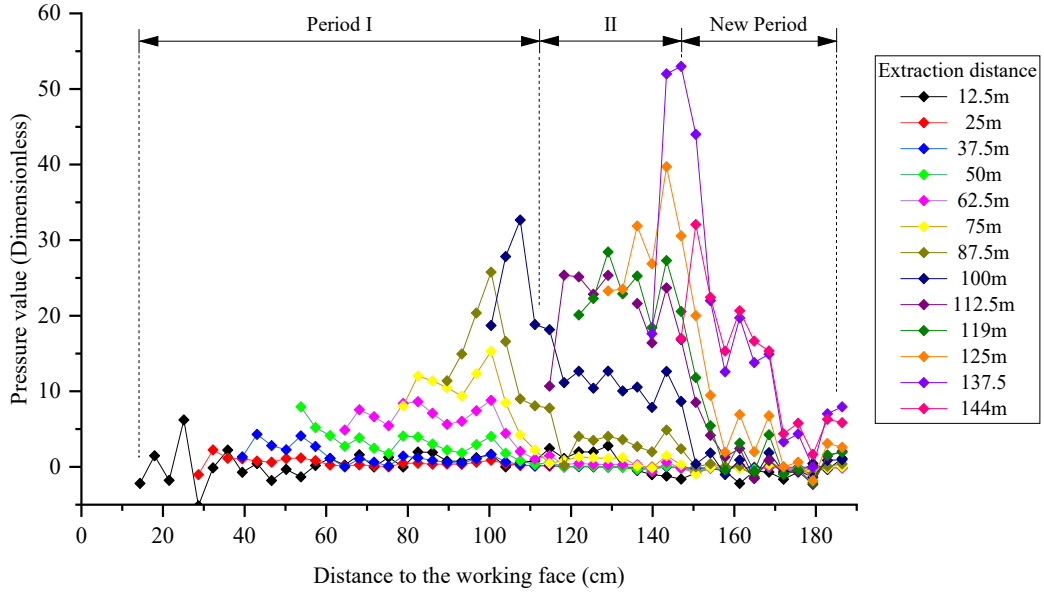
(2) Small-period weighting stage

The small-period weighting starts from the advancement of the working face from the open-off cut and ends when the first key stratum fractures initially (when the working face advances to 100 m). During the small-period weighting, the maximum weighting intensity is 32.67 MPa, and the weighting interval is 119 cm (Figure 4(b)). Combined with the overburden structure characteristics, during the small-period weighting, the load on the coal wall side comes from the additional stress caused by the rotation of the long cantilever structure of the first key stratum on the coal wall (Figure 5(a)). When the working face advances to 119 cm, the long cantilever structure cuts off, the small-

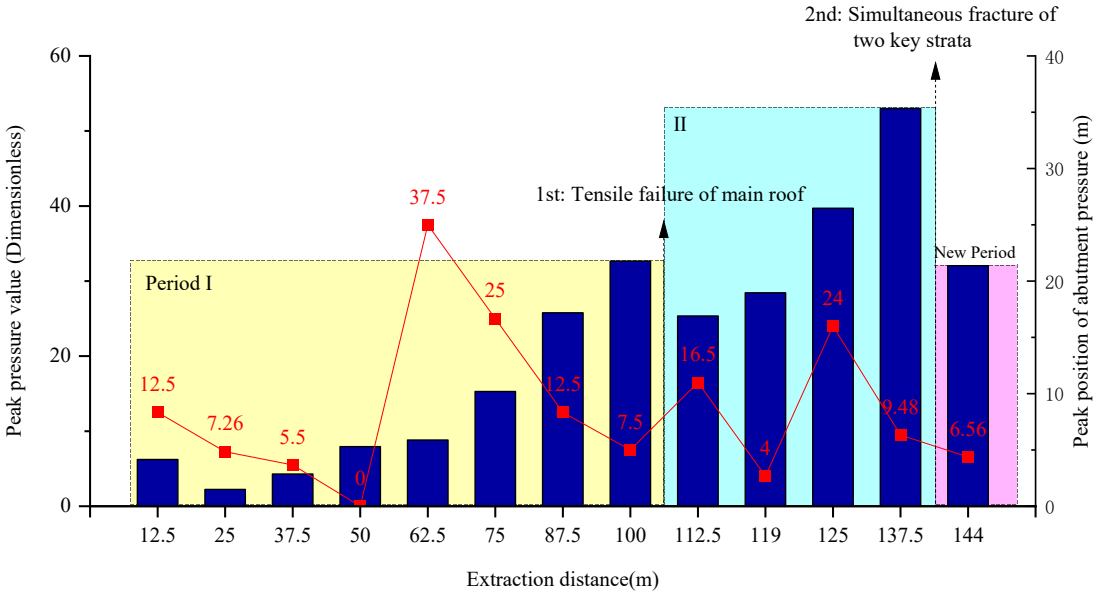
period weighting ends, and the abutment pressure decreases from 32.67 MPa to 25.35 MPa, with a decrease of 22.41%. On the whole, the small-period weighting has the characteristics of long duration and low weighting intensity.

(3) Large-period weighting stage

When the working face advances to 144 m, the large and small structures fracture simultaneously, resulting in sudden overburden fracture, and the working face enters the large-period weighting stage. The large-period weighting starts after the initial fracture of the first key stratum and ends with the joint fracture of the directly overlying double key strata (when the working face advances to 137.5 m). During the large-period weighting, the maximum weighting intensity is 53 MPa, and the weighting interval is 29.3 cm (Figure 4(b)), which has the characteristics of short duration and high weighting intensity. From the perspective of overburden structure characteristics, compared with small-period weighting, the load layer during large-period weighting is the voussoir beam structure formed by strata in the 20~80 m range. On the eve of large-period weighting (instant of structural rotation), the load on the coal wall side comes from the superposed additional stress caused by the rotation of the short cantilever structure of the first key stratum and the voussoir beam structure formed by the second key stratum and its controlled overburden (Figure 5(b)).



(a) Stress distribution curves at different advancing distances



(b) Peak stress and its position at different advancing distances

Figure 4 Characteristics of large and small periodic weighting.

4 Roof load transfer law of directly overlying double key strata

4.1 Overburden activity characteristics and weighting characteristics

The ground pressure behavior of the working face originates from overburden fracture and structural adjustment movement. As the key stratum that controls overburden movement, its fracture and subsequent formed overburden structure directly determine the ground pressure behavior of the working face. For shallow buried ultra-large mining height working faces with directly overlying double key strata, the particularity of overburden movement and ground pressure mechanism is mainly reflected in the following two aspects: (1) First, the increase of caving zone range in ultra-large mining height mining makes the lower key stratum fail to form a stable structure with adjacent rock blocks after fracture. As a result, after the lower key stratum fractures, the load acts on the support and the occlusal point throughout the process until the working face pushes past the fracture line, thus forming a long-distance periodic weighting. (2) Second, there are characteristics of large and small periodic weighting. Due to the different loads on the upper and lower key strata, their fracture intervals are also different. Usually, the fracture interval of the second key stratum is larger than that of the first key stratum, resulting in asynchronous fracture of the two strata. When only the lower key stratum fractures, small-period weighting occurs in the working face, with small fracture interval, and the load layer is only the first key stratum and the underlying strata, with low intensity. When the upper key stratum fractures, its fracture will cause synchronous fracture of the overlying strata controlled by it. All these loads will act on the working face supports through the immediate roof, leading to strong weighting of the working face.

According to the results of physical similarity simulation experiments, under the condition of directly overlying double key strata in ultra-large mining height working face, the periodic weighting mechanism of the working face is the small-period weighting dominated by the sliding instability of the long cantilever structure formed by the lower first key stratum, and the large-period weighting dominated by the rotation instability of the voussoir beam structure formed by the second key stratum and its controlled overlying strata. Therefore, for the calculation of support working resistance in ultra-large mining height fully mechanized face, it should be calculated according to the structural form formed by the key stratum, so that the results can meet the roof control requirements during actual mining. The following analyzes the support working resistance for different fracture structures of the lower (first layer) and upper (second layer) key strata.

4.2 Mechanical analysis of roof structure in small-period weighting

When the upper key stratum lags behind the lower key stratum in fracture and instability, small-period weighting is formed in the working face. When mining in shallow buried ultra-large mining height working face with directly overlying double key strata, the first key stratum of overburden forms a cantilever beam structure after fracture. In the early stage of block fracture, all the weight load of the fractured rock block acts on the hinge point and the support through the immediate roof, and the working face starts to weight. The overburden structure of small-period weighting is shown in Figure 6(a). When the working face continues to advance until it completely crosses the fracture line, the fractured rock block collapses behind the support, and the rock block movement will not affect the support, and the small-period weighting ends.

It can be seen from the overburden structure of small-period weighting that the fracture movement form of the lower key stratum is cantilever beam type periodic fracture. During the periodic weighting process dominated by it, the fractured rock block B1 can never form a stable structure. Therefore, the support resistance should ensure that block B1 does not undergo sliding instability, and at the same time, it should have a high setting load to avoid separation between B1 and the upper strata, block the further development of the fracture line, and cause the complete failure of the hinge point as shown in Figure 6(b). In addition, the setting load should also ensure the stability of the hinged structure of the second key stratum.

Therefore, in the small-period weighting stage dominated by the first key stratum, the working resistance should include two parts: the weight of strata in the caving zone and the balance force used to balance the second hinged structure. The weight load of strata in the caving zone includes the weight load Q1 of the cantilever beam fracture structure formed by the first key stratum and the weight load QZ1 of the underlying immediate roof rock mass. The balance force QPH1 of the hinged structure can be calculated according to the "voussoir beam" structure theory formula. Therefore, the calculation formula of working resistance during small-period weighting is obtained:

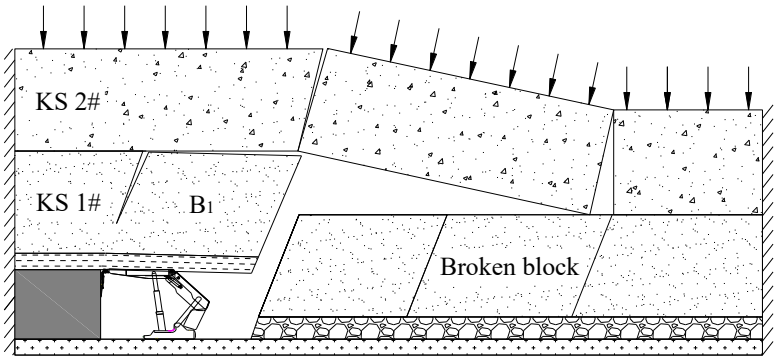
$$P_1 = Q_1 + Q_{ZI} + Q_{PHI}$$

Among them,

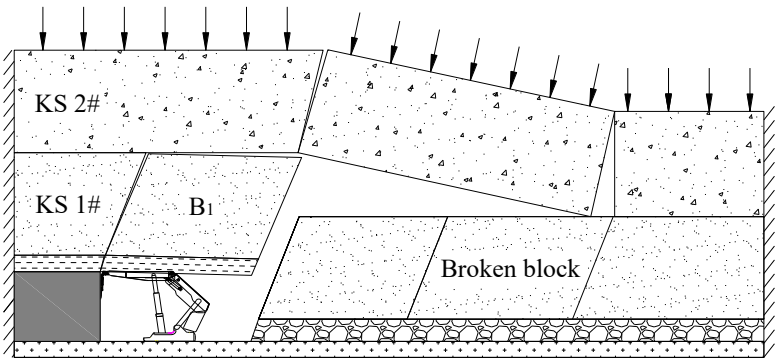
$$Q_1 = Bl_1h_1\gamma,\quad Q_{z1} = \mathrm{Bl_k}\sum \mathrm{h_i}\gamma$$

$$\mathrm{Q}_{PH1} = \left[2 - \frac{\mathrm{l}\tan(\varphi - \theta)}{2(\mathrm{h} - \delta)}\right]\mathrm{Q_0B}$$

In the formula, P_1 is the working resistance during small-period weighting caused by the fracture of the first key stratum; Q_{PHI} is the balance force required to maintain the balance of fractured rock blocks of the second key stratum; l_1 is the length of rock block; φ and θ are the friction angle between rock blocks and the fracture angle of rock blocks respectively; h_1 is the thickness of rock block; δ is the subsidence of hinged rock blocks of the second key stratum; Q_0 is the load of the fractured rock block of the key stratum itself and the upper controlled strata; γ is the bulk density of rock stratum; B is the support width.



(a) Initial rotation stage of block B1



(b) Condition of further development of fracture line of block B_1 due to insufficient support setting load

Figure 6 Calculation model of support working resistance during small-period weighting.

4.3 Mechanical analysis of roof structure in large-period weighting

Generally, the fracture interval of the second key stratum is larger than that of the first key stratum, that is, the periodic fracture of the second key stratum lags behind the first one. As a result, after the lower key stratum fractures, the upper key stratum fractures after the working face advances a certain distance. When the cumulative periodic fracture length of the lower key stratum reaches the periodic length of the upper key stratum, it will cause synchronous movement of the first key stratum, the second key stratum and the overlying strata groups controlled by them, and the load layer range will not be limited to the lower key stratum group. At this time, severe ground pressure behavior will occur in the working face. The roof overburden structure during large-period weighting is shown in Figure 7.

It can be seen from the overburden structure of large-period weighting that the support load during large-period weighting consists of three parts: the weight load Q_{Z2} of immediate roof strata, the weight load Q_2 of fractured rock blocks of the first key stratum, and the balance force Q_{PH2} for balancing the hinged structure of the second key stratum.

Therefore, in the large-period weighting stage caused by the joint fracture of upper and lower key strata, the support load calculation formula is:

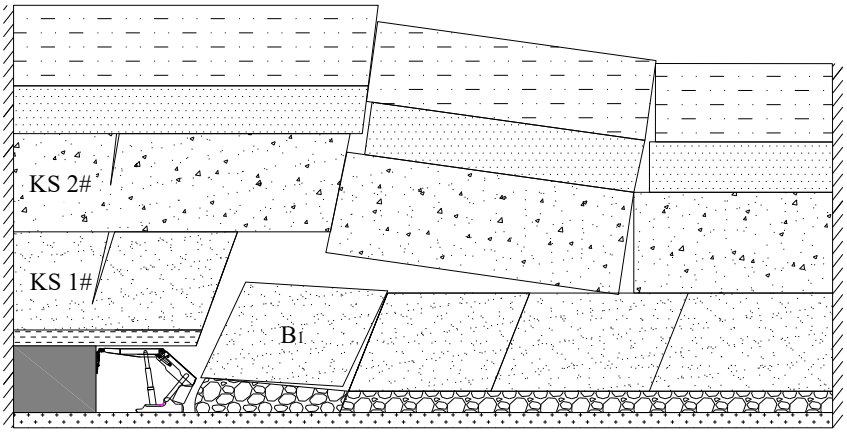
$$P_2 = Q_2 + Q_{Z2} + Q_{PH2}$$

Among them,

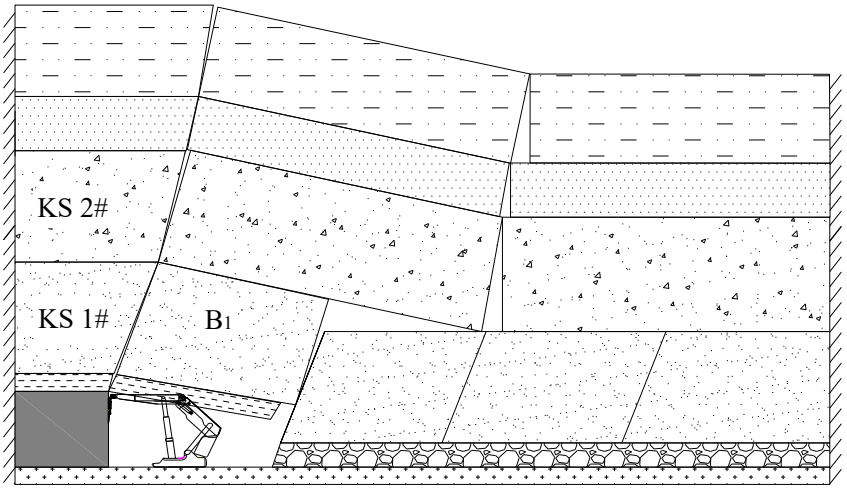
$$Q_2 = Blh_2\gamma, \quad Q_{z2} = \mathrm{Bl_k} \sum \mathrm{h_i}\gamma$$

$$\mathrm{Q}_{PH2} = \left[2 - \frac{\mathrm{l}\tan(\varphi - \theta)}{2(\mathrm{h} - \delta)}\right]\mathrm{Q_0B}$$

In the formula, Q_{PH2} is the balance force required to maintain the balance of fractured rock blocks of the second key stratum; l is the length of rock block; φ and θ are the friction angle between rock blocks and the fracture angle of rock blocks respectively; h is the thickness of rock block; δ is the subsidence of hinged rock blocks of the second key stratum; Q_0 is the load of the fractured rock block of the second key stratum itself and the overburden controlled by it; γ is the bulk density of rock stratum; B is the support width.



(a) Early stage of upper structure movement during large-period weighting



(b) Late stage of upper structure movement during large-period weighting

Figure 7 Calculation model of support working resistance during large-period weighting.

4.4 Calculation of working face support load

In summary, when calculating the support resistance of ultra-large mining height working face, the above three structural forms of key strata should be comprehensively considered. For the determination of 10 m support working resistance of 122104 working face, since the working face presents the above three structural forms at different stages, the support resistance under each structural form should be calculated, and finally the value should be taken according to the most dangerous situation.

For the 122104 working face, mining height m = 10 m, support roof control distance l_k = 7.0 m, hydraulic support width B = 2.4 m, equivalent immediate roof thickness $\sum h_i$ = 30.4 m, h_1 = 21.0 m, h_2 = 9.4 m, take equivalent immediate roof fracture angle α, equivalent immediate roof "short cantilever beam" length l= 9.3 m, lower key stratum thickness h_3 = 22 m, upper key stratum thickness h_5 = 22 m, average small-period weighting interval i.e. lower key block length L_1 = 16.3 m, average large-period weighting interval i.e. upper key block length L_2 = 24.5 m, rock stratum fracture angle β = 66 ° , take lower key stratum key block rotation angle θ = 10 °, upper key stratum key block rotation angle θ' = 8 °, load layer thickness h_z = 24.5 m, average bedrock bulk density γ = 25 kN/m³, take K_G = 0.5, K_P = 1.3.

Substituting into the calculation formulas of P_0, P_1 and P_2, the working face support load in the initial mining stage is 11000 kN, the support load in the small-period weighting stage is 15000 kN,

and the support load in the large-period weighting stage is 30000 kN. The support model used in the 122104 working face is ZY29000/45/100D, and its maximum support resistance is 29000 kN. That is, the existing supports of the working face cannot meet the bearing capacity in the large-period weighting stage. According to the key block analysis, pre-splitting work should be carried out on the hard roof, especially the second key stratum, to reduce the height of the load layer.

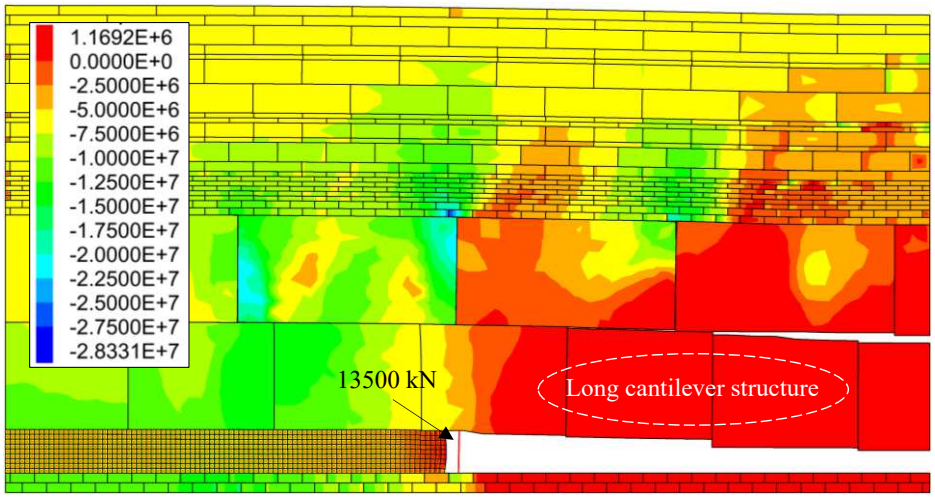
5 Numerical simulation of overlying strata structure and support working resistance

On the basis of physical simulation results, the Universal Distinct Element Code (UDEC) was adopted to conduct numerical analysis on the overlying strata structure and working resistance of hydraulic supports at the working face, as shown in Figure 8. The numerical simulation results are in good agreement with those from physical similar simulation. Specifically, the lower key stratum moves in a sliding subsidence pattern with a subsidence magnitude of 8 m during periodic weighting, and the corresponding overlying strata presents a stepped voussoir beam structure. After fracture, rock blocks of the upper key stratum are hinged with adjacent blocks to form a voussoir beam structure.

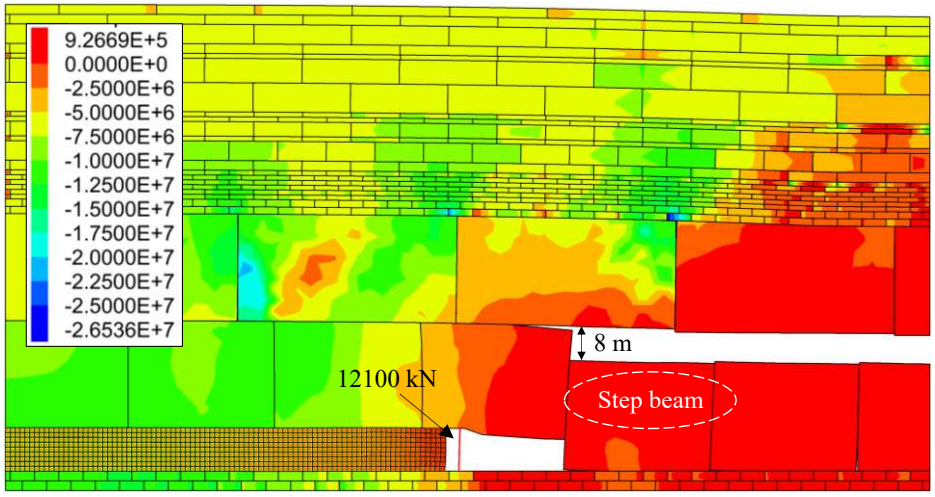
At different advance stages, the dual key strata above the working face exhibit four structural configurations as follows:①Long cantilever structure before the initial fracture of the lower key stratum; ②Stepped voussoir beam structure after periodic fracture of the lower key stratum; ③ "Lower stepped voussoir beam – upper voussoir beam" structure under synchronous fracture of the upper and lower key strata; ④ "Lower cantilever – upper voussoir beam" structure under asynchronous fracture of the upper and lower key strata.

It can be concluded that for mining under directly overlying dual key strata in super-high mining height working faces, the weighting intensity at the working face is governed by the loads transmitted to hydraulic supports by the above four types of overlying strata structures.

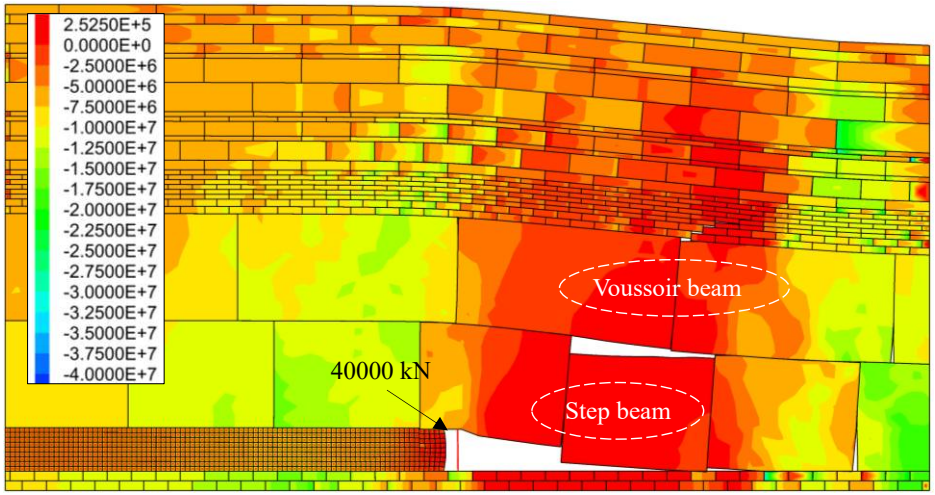
Numerical results indicate that the load transferred from overlying strata to supports is 13500 kN under the long cantilever structure prior to initial fracture of the lower key stratum; the support working resistance decreases to 12100 kN under the stepped voussoir beam structure after initial fracture of the lower key stratum. In contrast, the support resistance reaches 40000 kN when synchronous fracture occurs in the two key strata, representing the most severe period for underground pressure control at the working face, where the load exceeds the bearing capacity of the adopted supports.



(a) Long cantilever structure prior to initial fracture of the lower key stratum



(b) Stepped voussoir beam structure after initial fracture of the lower key stratum



(c) Structure of "lower stepped voussoir beam – upper voussoir beam" under synchronous fracture of upper and lower key strata

Figure 8 Overlying strata structure and support resistance at different stages.

6 Experiment on strong ground pressure control by roof pre-splitting

6.1 Design of hard roof pre-splitting experiment

For the situation of directly overlying double key strata in ultra-large mining height working face, if the ground pressure control means of the working face is limited to improving the rated working resistance of supports, it can no longer effectively cope with it. It is necessary to carry out pre-splitting work on the hard roof, especially the second key stratum, to reduce the weighting interval and realize pressure-relief mining. For this reason, a verification experiment of hard roof pre-splitting effect was designed. In this experiment, only the lithology of the two key strata with 44 m thickness overlying the working face was changed to simulate the effect of hard roof pre-splitting. The pre-splitting horizon and experimental model are shown in Figure 9.

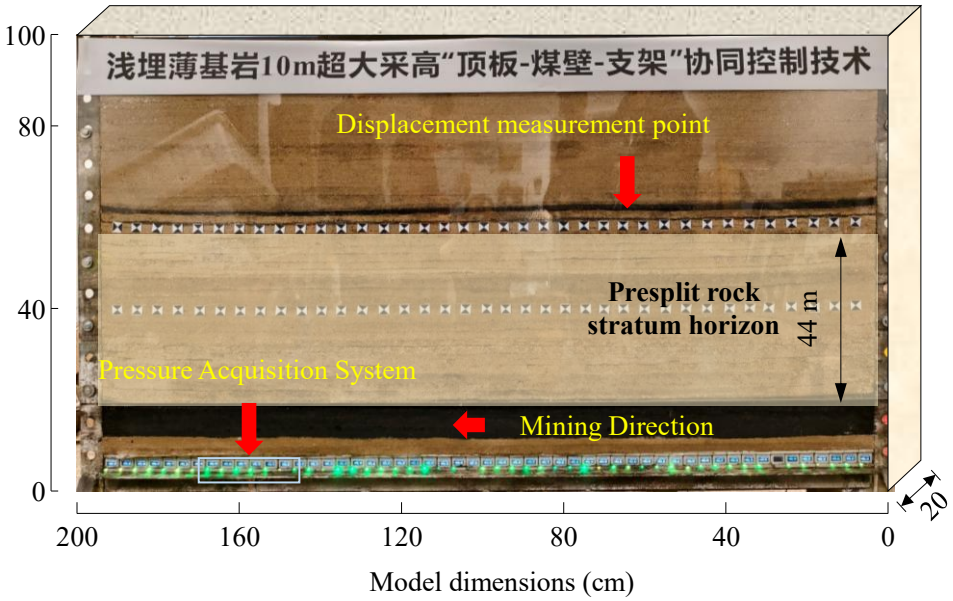
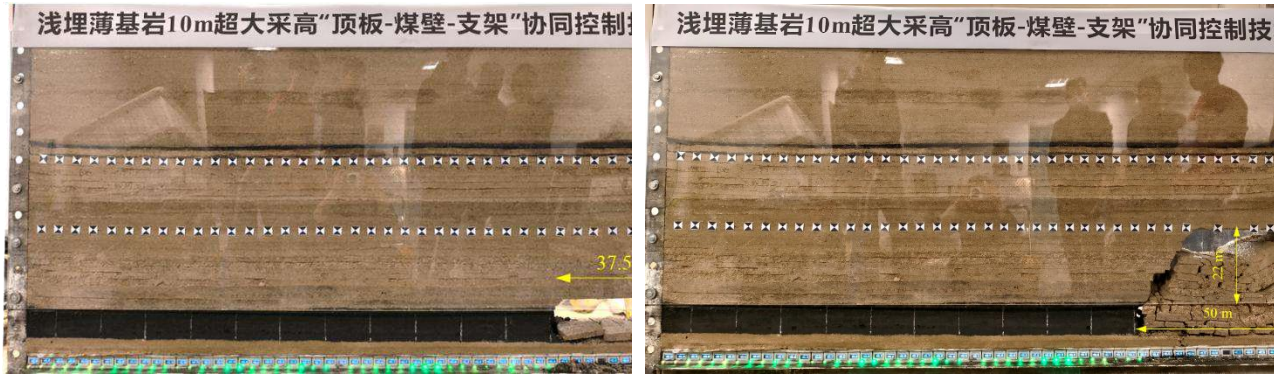


Figure 9 Experimental model of hard roof pre-splitting.

6.2 Experimental results

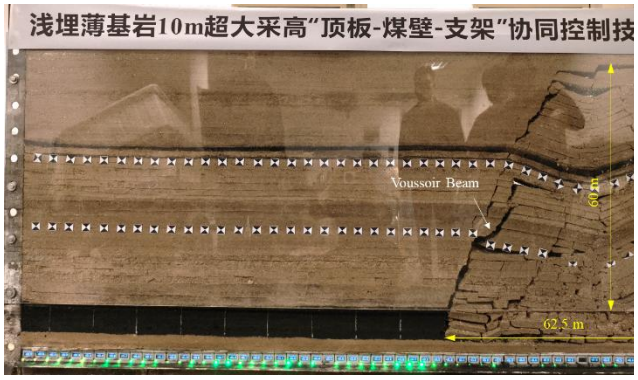
The movement characteristics of overburden at each stage after roof cutting and pre-splitting are shown in Figure 10. It can be seen from the figure that after implementing hard roof pre-splitting, the initial fracture interval of the first key stratum is reduced to 50 m, which is 57.98% less than the 119 m fracture interval without pre-splitting. The height of the load layer controlled by it in the initial mining stage remains unchanged, still 22 m. The periodic weighting interval is reduced to 12.5 m, which is 52.97% less than the 26.58 m interval without pre-splitting (Figure 10(b)). Then, when advancing to 62.5 m, the second key stratum of overburden undergoes initial fracture, which is 56.6% less than the 144 m fracture interval without pre-splitting. After fracture, the roof can still form a voussoir beam structure (Figure 10(c)). The periodic weighting interval is reduced to 20 m, which is 60.78% less than the 51 m interval without pre-splitting (Figure 10(d)).

In terms of working face weighting, the stress concentration coefficient table of two passes of physical similarity simulation is shown in Figure 11. It can be seen from the figure that after hard roof pre-splitting, the stress concentration coefficient decreases with each advancement, and the maximum stress concentration coefficient decreases from 4.23 to 3.39, a reduction of 19.86%.

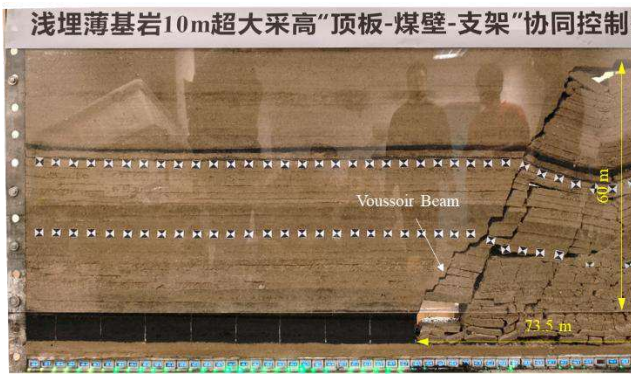


(a) Advancing to 37.5 m

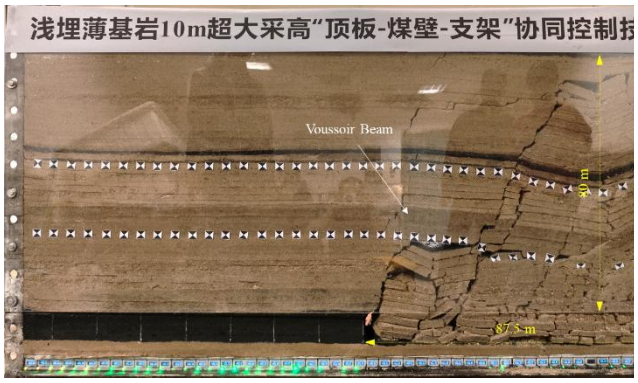
(b) Advancing to 50 m



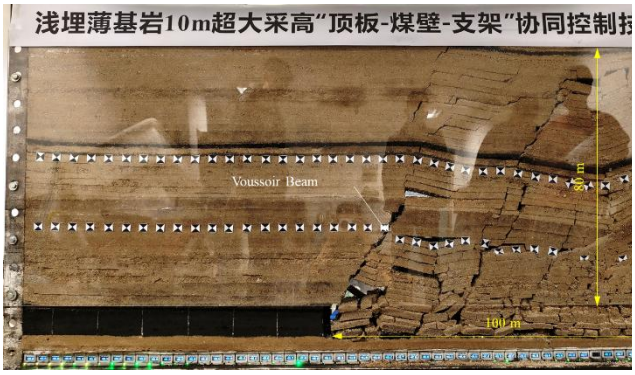
(c) Advancing to 62.5 m



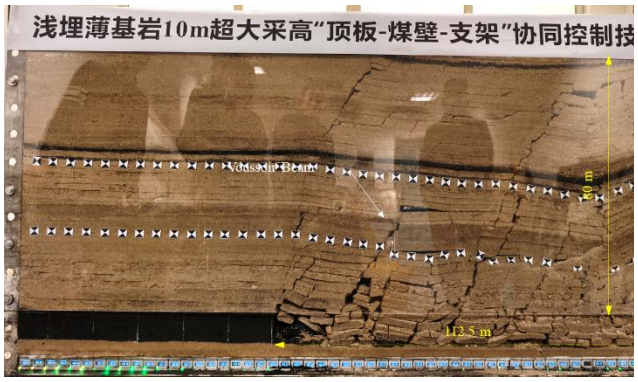
(d) Advancing to 73.5 m



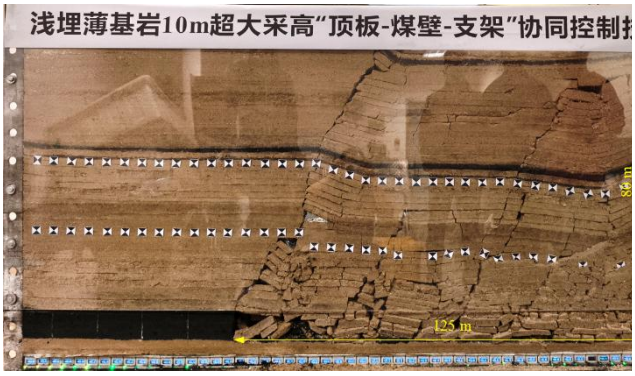
(e) Advancing to 87.5 m



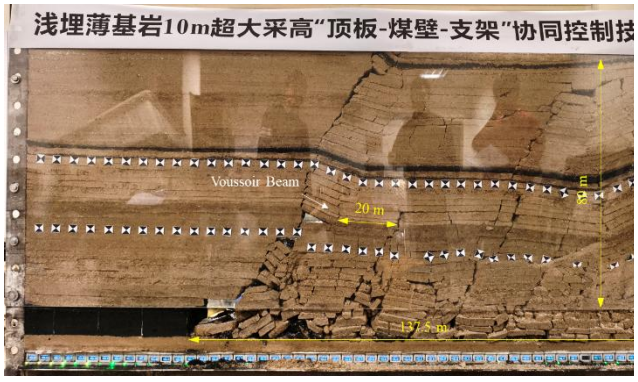
(f) Advancing to 100 m



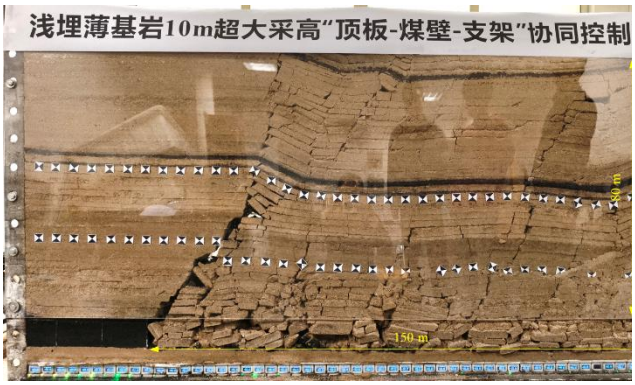
(g) Advancing to 112.5 m



(h) Advancing to 125 m

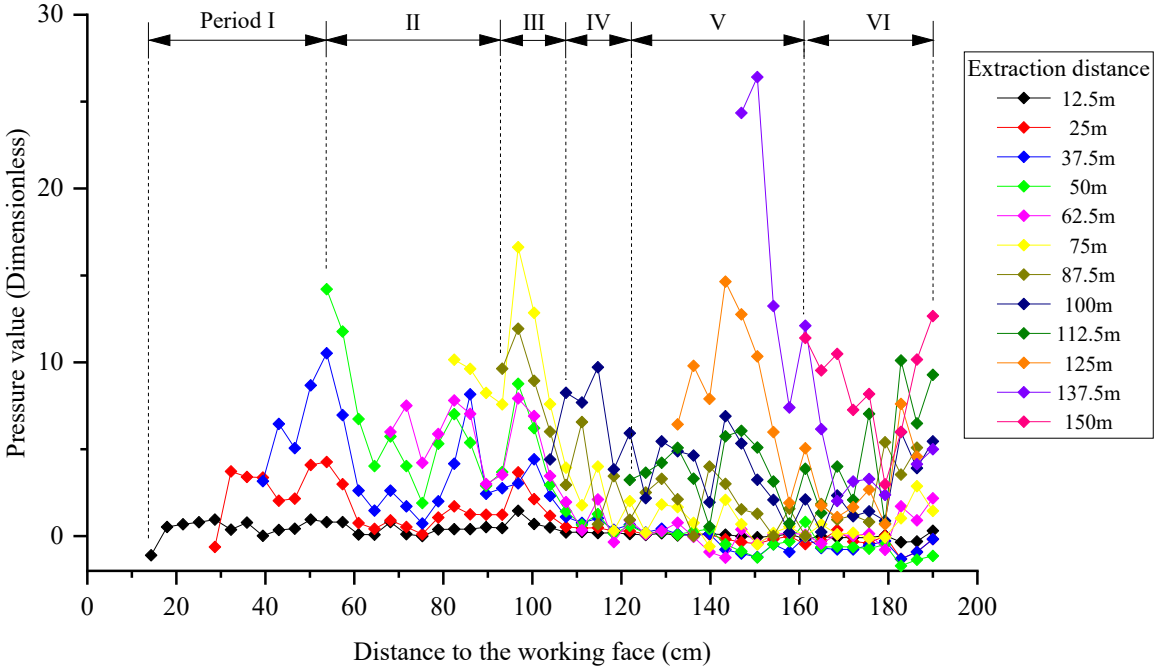


(i) Advancing to 137.5 m

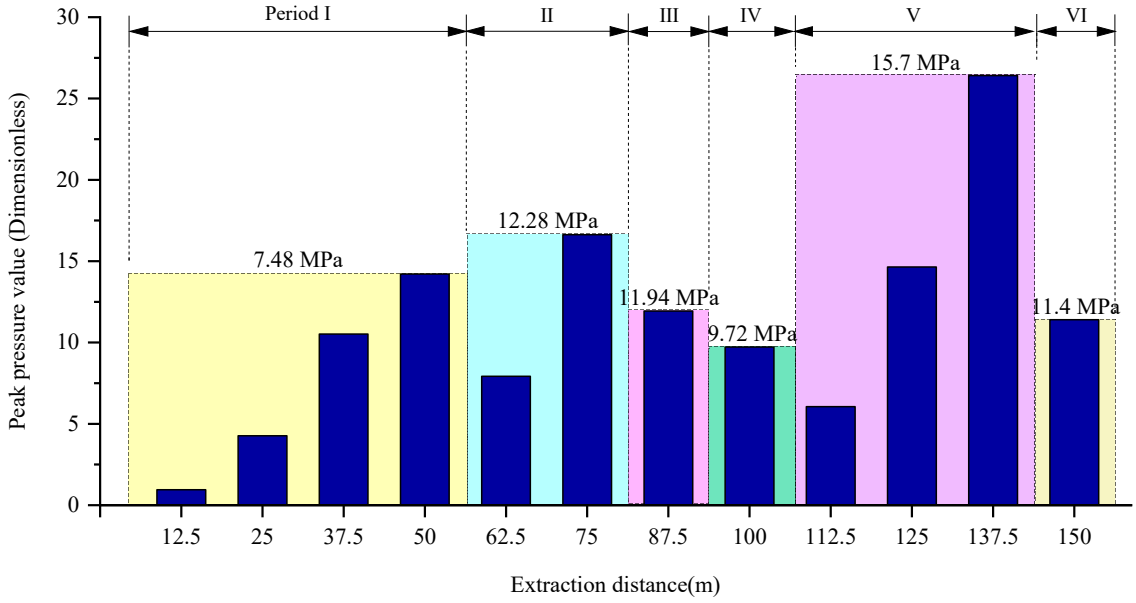


(j) Advancing to 150 m

Figure 10 Overburden movement characteristics after roof cutting and pre-splitting.



(a) Stress distribution curves at different advancing distances



(b) Peak stress and its position at different advancing distances

Figure 11 Weighting characteristics after roof cutting and pre-splitting.

7 Engineering example verification

7.1 Hard roof hydraulic fracturing weakening scheme

According to the previous analysis, the dynamic and static load superposition caused by the simultaneous fracture of directly overlying double-layer hard thick roof is the main reason for the strong ground pressure behavior of the working face. Conventional means such as improving the working resistance of hydraulic supports still have safety gaps in stope surrounding rock control. Implementing hard roof pre-splitting can reduce the exposed length of hard roof, promote the early fracture of hard roof, reduce weighting intensity and fracture interval, and at the same time reduce

the energy accumulation of thick hard roof, effectively alleviating the strong ground pressure behavior of the working face.

Specific construction scheme: In the advancing mileage of 5250 m ~ 4910 m of 122104 working face, drill sites are arranged in advance along the mining roadway to fracture four horizons within 340 m ahead of the working face, namely low position 14 m (5 holes) and 36 m (4 holes). The schematic diagram of hard roof pre-splitting scheme is shown in Figure 12.

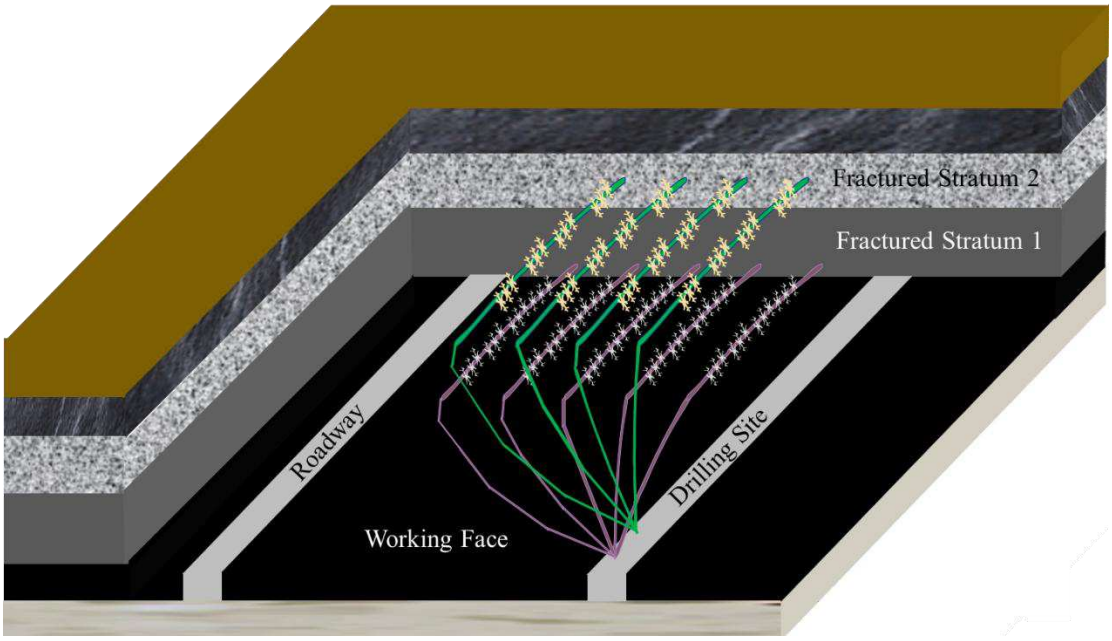


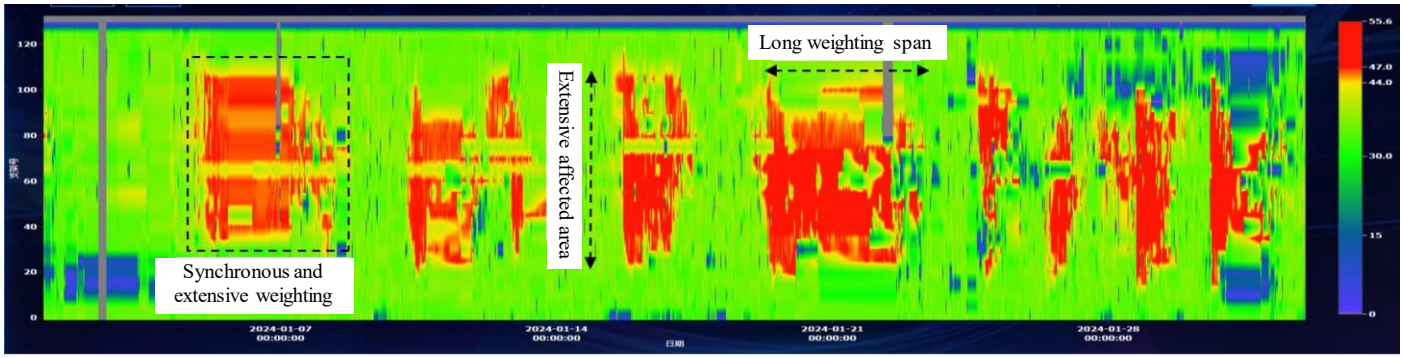
Figure 12 Scheme of hard roof pre-splitting.

7.2 Engineering verification of weighting interval and duration after hydraulic fracturing

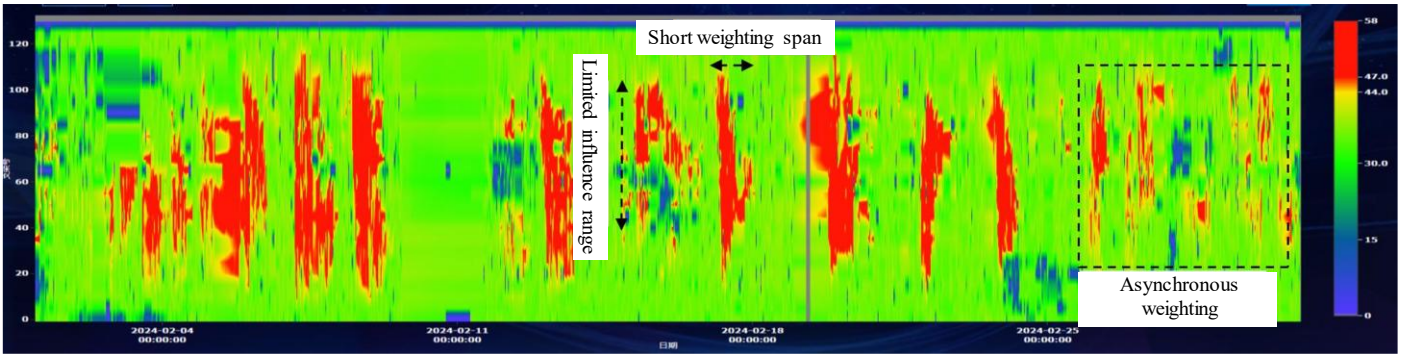
After implementing hard roof hydraulic fracturing weakening, the support working resistance during the advancement of the working face is continuously monitored, and the periodic weighting interval and duration and other weighting laws are summarized and analyzed.

(1) Overall situation

From February 1 to March 1, 2024, the 122104 working face advanced about 340 m (advancement degree 740~1060 m), and 23 weightings occurred. Compared with January 2024, during February (especially after February 11, mileage > 840 m), the working face weighting gradually presents the characteristics of "reduced influence range", "reduced synchronization", and "shortened duration", and the weighting intensity shows an obvious downward trend as a whole, as shown in Figure 13.



(a) Support resistance before fracturing



(b) Support resistance after fracturing

Figure 13 Contour maps of support resistance before and after hard roof pre-splitting.

(2) Periodic weighting interval and duration

As shown in Figure 14, from February 1 to March 1, 2024, during the period of working face advancement degree 740~1070 m: the periodic weighting interval ranges from 7.50 m to 32.7 m, with an average of 19.09 m; the weighting duration ranges from 4.4 m to 23.0 m, with an average of 10.63 m. Among them, since February 17 (advancement degree > 900 m), the weighting interval of the working face has shown a continuous decreasing trend as a whole.

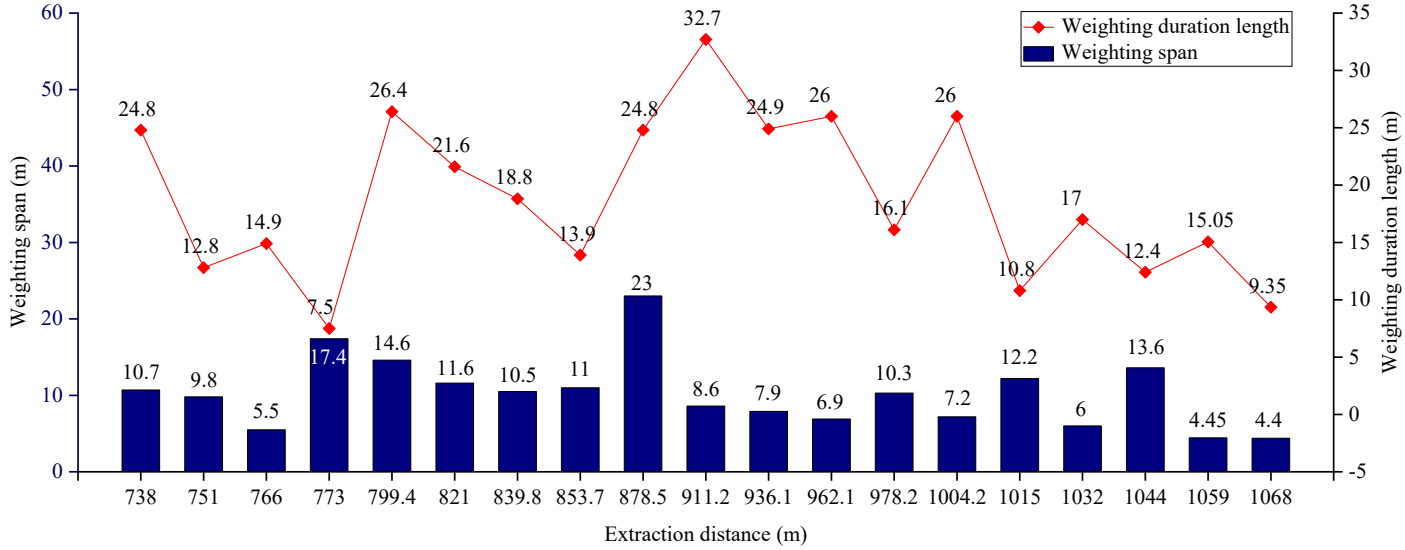


Figure 14 Periodic weighting interval and duration of the working face after hard roof pre-splitting.

8 Conclusions

(1) For shallow buried ultra-large mining height working face with directly overlying double key strata, the overlying strata are mainly stepped rock beams and voussoir beams.

(2) The stepped rock beam structure formed after the fracture of the lower key stratum controls the movement of overlying strata within 22 m, which is the main reason for the small-period weighting of the working face. After the upper key stratum fractures, it forms a voussoir beam structure. Its periodic rotation and subsidence may force the lower key stratum to fracture in advance, and drive the load of the overlying non-key strata to be transmitted to the working face, causing large-period weighting.

(3) The roof structure model of large mining height working face is established, and the theoretical calculation method of working face support working resistance is given.

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Competing interests

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Data availability statement

Data will be made available on request.