Reasonable stopping method and retracement channel support at fully mechanized top coal caving working face of 15 m extra-thick coal seam: A case study

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Abstract
Extra-thick coal seams are widely distributed in the Datong mine area in China. The rapid stopping of mining and the support withdrawal technology for extra-thick coal seams need to be developed urgently. The reasonable stopping top coal caving distance, main roof's fracture line position, and large section roadway during the stopping period (LSRSP) support method of the header face of 15 m extra-thick coal seam are systematically studied by using field measurement, experiment, numerical simulation, and similar material simulation methods. With the increase in stopping coal caving distance, the range of the medium and low displacement zone of the LSRSP overburden gradually expands. In contrast, the depth of the plastic zone decreases. The scope and intensity of the high-stress area of the overlying rock in front gradually decrease and shift from deep to the outside, while the peak stress area shifts from the top coal area to the coal rib of the retracement channel. Comparing the stopping of medium-thick and thick coal seam working face, the interaction between “main roof–unmined top coal–supports” is analyzed. The unique characteristics of the extra-thick coal seam working face are derived: when the stopping coal caving distance is shorter than the length of the key block, the dropped coal body cannot effectively restrict the movement of key blocks. Mutual compression and subsidence occur between key blocks, making the broken coal rock block squeeze into the supports. By the simulation study of each index, the stopping coal caving distance of the extra-thick coal seam is optimal when it is slightly larger than the length of the key block (i.e., the periodic weighting step), simultaneously, the main roof fracture line behind the supports is most favorable for stopping mining. After ensuring the stability of the LSRSP’s overburden structure, the differentiated support scheme of “controlled zoning–strength grading” was proposed, and the
scheme was modified and verified by simulating the support prestress field. After field practice, the roof of the retracement channel is better controlled in deformation under the joint horizontal and vertical support, the robust control effect of the combined anchor cable is noticeable, the integrity of the polyurethane network is more substantial, and the working face supports have successfully achieved a safe and rapid evacuation.

KEYWORDS
extra-thick coal seam, key block, retracement channel, stopping mining line, stopping top coal caving distance, subzone and graded support

1 | INTRODUCTION

In the Datong mining area of China, Carboniferous coal seams are being exploited and utilized on a large scale. The thick coal seam is a typical characteristic of Carboniferous coal seams. It is usually called an extra-thick coal seam when the thickness of the coal seam exceeds 8 m. However, the Datong mining area has developed to the mining of 15 m extra-thick coal seam at present, and more and more extra-thick coal seam working surfaces are gradually established. The technology of longwall comprehensive mechanized top coal caving mining (LCMTCCM) has been generally used in the mining of extra-thick coal seams. The research on related technologies of fully comprehensive caving working faces has become a hot spot in the industry.

Aiming at the technical research of extra-thick coal seam mining, Chi et al. studied the caving characteristics of top coal in comprehensive discharge mining and introduced the analytic hierarchy process-fuzzy discriminant method to predict it. He et al. successfully carried out in the Datong mining area, leaving an 8 m narrow coal pillar in LCMTCCM face of the extra-thick coal seam. Zhang et al. monitored the depth of floor damage caused by the mining-induced stress on the working surface of the extra thick coal seam on site. Guo and Yang studied the failure height, collapse characteristics, and failure structure of the overburden during the recovery process of the working face of the ultra-thick coal seam under the goaf. For the study of the roof of the extra-thick coal seam, Li et al. elucidated the evolution regularity of the mining stress in the extra-thick coal seam under the hard-top condition; Zhu et al. proposed using the overburden caving model to predict multi-layer hard roof based on key stratum theory; He et al. artificially cracked the hard roof using fracturing technology. In addition, the mining of extra-thick coal seams has gradually shifted to deep formations, and the mining technology has become more mature.

During the working face life cycle, it is indispensable to safely and efficiently mine extra-thick coal seams while stopping and withdrawing the supports at a suitable location is the most crucial step to end the cycle. The stopping mining line of the working face is also called the terminal mining line, which is the position where the longwall working face stops coal mining and withdraws the supports. The supports are evacuated from the retracement channel, and the supports’ area and the channel’s area form a large section of the roadway during the stopping period (LSRSP). For the study of the reasonable width of the coal pillar and the location of the stopping line at the working face, both Feng et al. and Xue et al. have used simulation methods; Zhou et al. adopted a similar model experiment method; Zhu et al. used the technique of seismic waves excitation stress fields. Aiming at the research on the control of the surrounding rock of the retracement channel at the stopping mining line, Yan et al. analyzed the reasons for the severe stratification, large surrounding rock deformation, and large-scale roof collapse in the retracement channel of the extra-thick coal seam; Fei and Jiang revealed the deformation and failure mechanism of surrounding rock from the perspective of the retracement channel structure of the extra-thick coal seams; Ma et al. adopted the technique of roof cutting and pressure releasing to suppress the large deformation of the surrounding rock of the channel. For the study of the pre-excavation retracement channel technology, Li et al. analyzed that under the influence of mining, the surrounding rock of the channel will undergo asymmetric deformation; Lv simulated the apparent stress transferring of coal columns on both sides of the retracement channel. On this basis, Li et al. developed the technology of pre-excavating double retracement channels on site.
The above research illustrates that the pre-extraction retracement channel is used to remove the supports at the stopping mining stage of the working face. Many difficulties are encountered in controlling the surrounding rock of the roadway. However, under the condition of the extra-thick coal seam, the application of this method becomes more and more difficult. At the same time, the withdrawing space of the supports is a large cross-section of the roadway (LSRSP), and it is only inappropriate to emphasize the support of the retracement channel and ignore the support of the supports’ roof. For the support study of large section roadway, Xie et al.\textsuperscript{38-41} proposed the bearing structure of roof anchorage rock beam; Gu et al.\textsuperscript{42} and Tai et al.\textsuperscript{43} both carried out simulation research on the deformation mechanism of the large span roof and surrounding rock; Meng et al.\textsuperscript{44} and Peng et al.\textsuperscript{45} proposed a support scheme for large-section coal roadway under the condition of crushing the surrounding rock. Some scholars have made some innovations in support of patterns, such as equal-width support, and multi-means combined support.\textsuperscript{46,47}

At present, no scholar has systematically studied the stopping mode of 15 m extra-thick coal seam, especially the key problems such as distance of stopping top coal caving, fracture line position, and LSRSP support, which directly affect the withdrawal of supports. Meanwhile, the lack of references for related projects seriously limits the further development of 10 million-ton coal mines. In this paper, based on the research background of stopping mining and withdrawing supports in 15 m extra-thick coal seam fully mechanized caving face in Datong mining area, through on-site monitoring, laboratory experiments, and multi-means simulation methods, the overburden condition of LSRSP at different distances of stopping top coal caving is analyzed according to multiple indexes. In addition, a detailed numerical and physical simulation is carried out on the relationship between the main roof fracture line and the supports. The interaction model of “main roof–non-mined top coal–supports” in the extra-thick coal seam working face is established to obtain a reasonable stopping method for the 15 m extra-thick coal seam working face and ensure the stability of the overlying rock structure. Then, depending upon the site engineering conditions, drilling peepholes, pre-stress field analysis correction, and other methods, LSRSP surrounding rock zoning analysis, and put forward the “control zoning—strength classification” differentiated support technology. After implementation on-site, the supports of the working face of the extra-thick coal seam can be withdrawn safely and quickly, which fills the research gap of withdrawal of the supports of the working face of the extra-thick coal seam.

2 | ENGINEERING BACKGROUND

There are numerous working faces of the extra-thick coal seam in the Datong mining area of China. This study takes the 15 m extra-thick coal seam working face as the research object. Furthermore, the method of stopping coal caving and supporting its working face at the stopping mining stage is investigated.

2.1 | Geological analysis of 15 m extra-thick coal seam working face

N309 working face is located southwest of the No. 3 panel, with a length of 200 m and 118 top coal caving supports. As shown in Figure 1, the thickness of the coal seam in the area where the working face is located is 10.8–18 m, the average thickness is about 15 m, the average dip angle is 1.5\degree, and the hardness of the coal seam is 1.59, and the joints are well developed.

The 15 m extra-thick coal seam is composed of No. 3 and No. 5 coal seams of the Carboniferous, and there is a gangue layer with a thickness of about 0.25 m between the two coal seams, which belongs to the co-mining of the two coal seams. It adopts the mining method of fully mechanized low-level top coal caving mining with retreating single strike longwall. The buried depth of the top coal caving face is about 580 m, the mechanized mining height is 3.9 m, the caving height is 11.1 m, and the mining and caving ratio is 1:2.8. Moreover, the immediate roof of the extra-thick coal seam is composed of sandy mudstone and coarse sandstone with a thickness of 7.95 m, the main roof is composed of sandstone with a thickness of 13.95 m, and there is a key stratum with a thickness of 18.67 m at 27.02 m above it.

From the geological conditions, it can be concluded that the mining of the working face is stopped under the “three-thick” environment of thick top coal, thick immediate roof, and thick main roof.

2.2 | Working conditions during the stopping period

2.2.1 | Stopping technique of working face

There are generally two kinds of stopping mining technology in coal mining working face in China: pre-excavating retracement channel and self-excavating retracement channel.\textsuperscript{35,36} As shown in Figure 2, (a) indicates that: excavation of the retracement channel and support in advance $\rightarrow$ working face and retracement channel are intersected $\rightarrow$ formation of stopping mining.
space for the withdrawal of supports. (b) indicates that: ordinary cutting coal to the expected stopping line → shearer in the working face excavates the retracement channel → shearer and scraper conveyor after withdrawal to form a retracement channel.

Because the stopping mining technology of the pre-excavating retracement channel needs to be presupported and well maintained, it is found that there are some supporting problems such as large deformation in the application of other working faces in this mine.
Therefore, this working face adopts a self-excavating retracement channel to stop mining and withdraw supports.

### 2.2.2 | Necessity of stopping coal caving

When stopping mining, it is generally necessary to stop coal caving at a certain distance in advance. As shown in Figure 3, stopping top coal caving reduces the main roof key block rotation angle $\theta$; the other is to provide support $q$ and lessen the burden of support and retracement channel. Reasonable stopping top coal caving distance is the key to stopping mining research.

### 2.2.3 | The support characteristics of LSRSP

In Figure 4, the working face will form a large cross-section space for the withdrawal of support during the stopping mining stage (LSRSP). Its support is different from that of the general roadway, mainly as follows: (1) the support time is distinctive, the LSRSP’s service period is short, only about 30 days; (2) the requirements of cross-section support are different, LSRSP does not require full-section support, but the support of roof and coal rib; (3) the focus of the roof is distinct. The roof of LSRSP support should not be too strong, while the roof of the retracement channel needs more substantial support, and the integrity of protection of roadway surrounding rock surface is emphasized at the same time.

The working face of the extra-thick coal seam has extra-thick top coal of 11.1 m, so it is necessary to study the LSRSP support system under this condition.

### 3 | EXPERIMENTATION AND SIMULATION

#### 3.1 | Experimentation and modeling

### 3.1.1 | In situ observations and experiments

To explore the mechanical properties of top coal and the pressure condition of the working face, samples were taken at the site for uniaxial experiments, and drilling peep hole observations and monitoring of pressure conditions at the working face were carried out.

As shown in Figure 5, the uniaxial compression test on the standard rock sample taken from the N309 comprehensive workings shows that the coal body strength of this seam is 24–30 MPa, which is relatively lower than other seams.

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**Figure 3** Schematic diagram of stopping coal caving before stopping mining. (A) No stop caving of fully mechanized caving face in extra-thick coal seam before stop mining. (B) Stop coal caving of fully mechanized caving face in extra-thick coal seam before stop mining.

**Figure 4** Support characteristics of the LSRSP. LSRP, large section roadway during the stopping period.
high. In addition, drilling peephole observations are carried out on the top of the supports to observe the crack development characteristics of extra-thick top coal. The results show apparent cracks in the top coal within 3.8 m; there are no apparent cracks in the 3.8–6.5 m section. Only local fracture zones exist; the borehole wall is gradually complete with the deepening of drilling, and there is no obvious crack. According to the results of the on-site investigation, the basic no-pressure time period of the working face is generally 1–3 days, and the working face can advance 6–18 m; the pressure period of the working face is 1–1.5 days, and the working face advances 6–9 m. Thus, the fracture step distance of the main roof is roughly 10–20 m in length. And the periodic weighting step distance of the working face is 12–27 m, with an average of 19.5 m.

3.1.2 | Numerical model for stopping mining in 15 m extra-thick coal seam

The discrete element numerical simulation method is used to establish a numerical model with the same size as the actual size in the field, and the ZF15000/27.5/42 support shield low-level top coal caving hydraulic support model is constructed in the same proportion, as shown in Figure 6. The model’s size is 360 m × 130.1 m, and the buried depth of the working face is about 580 m. So, the vertical stress at the upper...
boundary of the model is 12.9 MPa, and the lateral pressure coefficient is 1.2. In the model, the span of the stopping mining large section space is 12.1 m, and the distance between the two sides of the boundary is more than 150 m. Thus, the influence of the size effect can be eliminated.

3.2 | Numerical analysis in different distances of stopping coal caving

Seven different stopping coal caving distances (0, 5, 10, 15, 20, 25, and 30 m) are established for the simulation study, and the overlying rock block structure, displacement, surrounding rock stress, and plastic zone range are analyzed to obtain the relatively optimal distance.

3.2.1 | Comparison of overburden block structure

As shown in Figure 7, the structural regularities of overburden blocks with different stopping coal caving distances are as follows: (1) when the stopping coal caving distance is 0 m, the key block of the main roof falls as a whole and presses to the supports, and the roof of LSRSP breaks and sinks violently. (2) When the stopping coal caving distance is 5, 10, and 15 m, the subsidence of the key block of the main roof is “step-like.” The coal body of the LSRSP roof moves downwards as a whole. (3) When the stopping coal caving distance is 20, 25, and 30 m, the two key blocks of the main roof above it are not broken and are supported by the unmined coal body. The coal body of the LSRSP roof only has local deformation without overall subsidence and slip.

3.2.2 | Comparison of overburden displacement

Comparing the overlying rock displacement cloud map with different stopping coal caving distances shows pronounced displacement zoning (high displacement area, middle displacement area, and low displacement area) and the regularity of gradual decrease from gob to working face, as shown in Figure 8.

(1) When the stopping coal caving distance is 0, 5, and 10 m, the displacement of the rock mass above the support is significant, indicating that this part of the rock mass has fallen and squeezed supports, which seriously affects the withdrawal of support. (2) When the stopping coal caving distance is 15 m, the support of the unmined top coal limits the rotation of the key block, but its function is restricted, and the rock blocks are still squeezed to the support. (3) When the stopping coal caving distance is 20, 25, and 30 m, the range of the high displacement area decreases obviously, and the two main key blocks with rotation are supported by the unmined coal body and are in the middle and low displacement area.

![Fracture structure of the main roof and key layer at different stopping coal caving distances](image)

**Figure 7** Comparison of the block structure of overlying rock under different stopping coal caving distances. (A) 0 m, (B) 5 m, (C) 10 m, (D) 15 m, (E) 20 m, (F) 25 m, (G) 30 m.
3.2.3 Comparison of surrounding rock stress

The vertical stress and maximum shear stress commonly used in engineering are selected to analyze the stress state of LSRSP’s surrounding rock in extra-thick coal seam under different stopping coal caving distances.

**Vertical stress**

First, the vertical stress distribution of overlaying rock at different stopping coal caving distances is compared, as shown in Figure 9.

With the increase of stopping coal caving distance, the stress concentration degree and range in front of the working face gradually decrease. When the distance is
less than 15 m, the high-stress zone extends vertically and longitudinally in the rock mass ahead of the working face, and the peak stress is at the top coal on the lower side of the immediate roof, which is far from the coal wall of the working face. When the distance is more than 15 m, the high-stress zone decreases in the vertical extension, the high-stress zone shifts, and the stress maximum gradually shifts to the edge of the coal rib.

For a quantitative demonstration of the pattern, the data were monitored for 100 m forward of the midpoint of the channel's coal rib and the midpoint of the top coal, respectively, as shown in Figure 10.

(1) It can be seen from panel (a) in Figure 10 that the stress reduction area in front of the retracement channel gradually shifts to the outside of the coal rib with the increase of the stopping coal caving distance, and there is no stress reduction area when the distance is 25 m. Correspondingly, the peak stress point gradually increases and moves outwards, with a moving distance of about 3 m. (2) It can be seen from panel (b) in Figure 10 that with the increase of stopping coal caving distance, the stress reduction area and the peak stress point in front of top coal gradually shift to the left, where the peak stress point gradually decreases and the moving distance is about 7 m. (3) Comparing the two curves, the peak stress area in front of the retracement channel is significantly smaller than that of top coal. Therefore, the peak stress area of top coal gradually shifts to the front of the rib of the retracement channel, and the peak stress area is reduced.

**Figure 10** Stress monitoring of retracement channel and top coal. (A) Measuring line in the direction of vertical coal rib in the retracement channel. (B) Measuring line in the direction of vertical coal rib in the top coal.
Maximum shearing stress
To verify the regularity of stress transfer, the maximum shear stress of overburdened rock at different stopping coal caving distances is then compared and analyzed, as shown in Figure 11.

(1) When the stopping coal caving distance is 0, 5, and 10 m, the shear stress concentration area goes deep into the front coal and rock mass. The peak value of shear stress in the extra-thick coal seam in front of LSRSP is at the top coal, and its peak value gradually shifts to the outside. (2) When the stopping coal caving distance is more excellent than 15 m, the distribution of the shear stress concentration zone in the front coal rock body is significantly reduced, and the peak shear stress in the extra-thick coal seam in front of LSRSP gradually turns to the front of coal rib of the retracement channel. The increase of stopping coal caving distance leads to the transfer of stress peak point in the extra-thick coal seam, and the range of peak area is gradually reduced.

3.2.4 | Comparison of the plastic zone of surrounding rocks
To analyze the influence of the change of overlying strata stress under different stopping coal caving distances on the plastic zone, as shown in Figure 12, the plastic zone of overlying strata under each distance is analyzed.

(1) When the stopping coal caving distance is 0 m, the plastic zone in front of LSRSP and in front of top coal is the largest. (2) When the distance is 5, 10, and 15 m, the range of plastic zone in front of LSRSP and in front of top coal decreases gradually, but the top coal above LSRSP is basically all plastic damaged. (3) When the distance exceeds 20 m, the top coal appears as an entire area, and the surrounding rock plastic zone decreases. To analyze the decrease of the surrounding rock plastic zone of LSRSP with the increase of the distance, as shown in Figure 13, the maximum plastic zone distance in front of LSRSP and the plastic zone depth of the coal rib in the retracement channel are compared.

It can be seen from the fitting line equation that the reduction rate of the maximum plastic zone depth in front of LSRSP is 1.7 and that in front of the retracement channel is 1.6. However, when the stopping coal caving distance is greater than 20 m, the depth of the maximum plastic zone in front of the coal body is unchanged. When the distance is 20 and 25 m, the depth of the plastic zone in front of the retracement channel is consistent. This shows that when the distance increases to 20 m, the overall decrease of the plastic zone is more minor.

3.3 | Numerical analysis of the effect of main roof fracture line on mining stoppage
3.3.1 | Different fracture lines of the main roof
As shown in Figure 14, there are generally three types of relationship between the fracture line of the main
roof and the supports: (1) the main roof fracture line is in front of the supports, as shown in Figure 14A; (2) the main roof fracture line is above the supports, as shown in Figure 14B; (3) the main roof fracture line is located behind the supports, as shown in Figure 14C.

3.3.2 | Simulation comparison of different fracture lines

The various indicators of LSRSP covering rock under different fracture lines are analyzed by numerical simulation, and the distance chosen to stop coal discharge here is 20 m, as shown in Figure 15.

(1) When the fracture line of the main roof is located in front of the supports, the high-stress area of the vertical stress is the largest. The key block above the supports rotates, and there is a shear stress concentration area, resulting in plastic failure of all the top coal, apparent subsidence of top coal, and severe compression of supports. (2) When the fracture line of the main roof is just above the supports, the boundary of the overlying strata displacement area is also above the supports, and the strength of the vertical stress is the highest. The key block above the supports rotates, and the strength of the shear stress concentration area is the highest. Similarly, all the top coal is plasticized and obviously sinks, and the supports are severely compressed. (3) When the fracture line of the main roof is behind the supports, the boundary of the overlying strata displacement area is also behind the supports, the strength of the vertical stress is the lowest, the key block above the supports is stable, and the strength of the shear stress concentration area is the lowest, the top coal has an entire region and the subsidence is minor, the supports are in good condition.

3.4 | Physical similarity simulation of stopping mining in extra-thick coal seam

The physical similar material ratio model experiment was conducted to grasp the overlying strata structure and the effect of stopping coal caving in the 15 m extra-thick coal seam.
3.4.1 Establishment of the similar model experiment

The 1:100 similarity model is built on a sizeable two-dimensional similarity simulation platform in the laboratory, as shown in Figure 16. The model was excavated from right to left, and an equal proportion of plastic support was used to simulate the actual support. During the excavation, transparent plastic plates were installed on both sides to prevent the overlying rock block’s lateral collapse after the extra-thick coal seam was excavated.

3.4.2 Fracture characteristics of overburden rock at different distances of stopping coal caving

According to the numerical simulation research and the main roof weighting step, three groups of stopping coal caving distances are set for research, as shown in Figure 17.

1. As shown in Figure 17A, the stopping caving distance is short, and there is a significant gap above it, which gives the key block of the main roof more significant rotation and subsidence space; the rear key block squeezes the scattered block of the main roof to the supports.

2. As shown in Figure 17B, the unmined bottom coal fully supports the key block so that it has no movement space; the rear key block is also subjected to a specific load so that it still squeezes the back area; at this time, the supports were evacuated smoothly.

3. As shown in Figure 17C, the distance is too long, the two key blocks of the main roof are fully supported, there is no continuing motion space, and the rotation angle is close to the flat angle; similarly, the support is removed smoothly, but it will also cause waste of coal and reduce the recovery rate.

3.4.3 Fracture characteristics of overburden rocks under different fracture line locations

Based on the relationship between the main roof fracture line and the supports, the overburden and supports conditions at different fracture line locations were studied, as shown in Figure 18.

1. As shown in Figure 18A, when the fracture line is located in front of the supports, the key block above the supports has a slight turning angle, but all the supports are squeezed and seriously damaged, which is difficult to pull out the supports during the experiment.

2. As shown in Figure 18B, the unmined bottom coal fully supports the key block so that it has no movement space; the rear key block is also subjected to a specific load so that it still squeezes the back area; at this time, the supports were evacuated smoothly.

3. As shown in Figure 18C, the fracture line is located behind the supports. Meanwhile, the turning angle of the key block is significant, but it all acts behind the supports. The supports are under a stable cantilever structure, and their
| Indicators       | The fracture line is in front of the support | The fracture line is directly above the support | The fracture line is behind the support | Gradient value |
|------------------|---------------------------------------------|-----------------------------------------------|----------------------------------------|----------------|
| Displacement     | ![Image](https://via.placeholder.com/150)  | ![Image](https://via.placeholder.com/150)     | ![Image](https://via.placeholder.com/150) | Displacement/m |
|                  | ![Image](https://via.placeholder.com/150)  | ![Image](https://via.placeholder.com/150)     | ![Image](https://via.placeholder.com/150) |                |
| Vertical stress  | ![Image](https://via.placeholder.com/150)  | ![Image](https://via.placeholder.com/150)     | ![Image](https://via.placeholder.com/150) | Vertical stress/Pa |
|                  | ![Image](https://via.placeholder.com/150)  | ![Image](https://via.placeholder.com/150)     | ![Image](https://via.placeholder.com/150) |                |
| Maximum Shear    | ![Image](https://via.placeholder.com/150)  | ![Image](https://via.placeholder.com/150)     | ![Image](https://via.placeholder.com/150) | Maximum Shear/Pa |
|                  | ![Image](https://via.placeholder.com/150)  | ![Image](https://via.placeholder.com/150)     | ![Image](https://via.placeholder.com/150) |                |
| Block state      | ![Image](https://via.placeholder.com/150)  | ![Image](https://via.placeholder.com/150)     | ![Image](https://via.placeholder.com/150) | Block state    |
|                  | ![Image](https://via.placeholder.com/150)  | ![Image](https://via.placeholder.com/150)     | ![Image](https://via.placeholder.com/150) |                |

**Figure 15** Comparison of simulation results for different fracture line locations

**Figure 16** Physical similarity ratio model experiment
load is small and can be evacuated smoothly. Therefore, the safe stopping mining position should ensure that the main roof fracture line is behind the supports; that is, the supports should be removed in the non-weighting state in the field.

3.5 | Reasonable distance of stopping coal caving for 15 m extra-thick coal seam working face

3.5.1 | Characteristics of stopping coal caving at working face in extra-thick coal seam

According to the regularity that the above indexes change with the increase of stopping coal caving distance in numerical simulation, the interaction relationship of "main roof–unmined top coal-supports” in an extra-thick coal seam is analyzed in Figure 19.

(1) When the distance of stopping coal caving is 0, the gob area of extra-thick coal seam gives the main roof full swing and sinking space. Thus, the supports bear impact and extrusion, resulting in accidents such as supports pressing and dumping. (2) When the distance of stopping coal caving is 0.5 and 0.75 times the weighting step, the key block above the unmined top coal is supported to a certain extent, but the gob area of the extra-thick coal seam still gives a large space, and the key block at the backside is oppressed and further sinks, which makes the unmined top coal squeeze into the supports under pressure from the side and above. And it is still not conducive to the support’s removal. (3) When the distance of stopping coal caving is greater than the weighting step, the key blocks are fully supported,

FIGURE 17 The breaking state of overlying strata under different stopping coal caving distances. (A) The distance of stopping coal caving is 0.5 times the weighting step. (B) The distance of stopping coal caving is equal to the weighting step. (C) The distance of stopping coal caving is 1.5 times the weighting step.

FIGURE 18 Breakage status of overburden rocks under different fracture line locations. (A) The fracture line of the main roof is in front of the support. (B) The fracture line of the main roof is directly above the support. (C) The fracture line of the main roof is behind the support.
(A) The distance of stopping coal caving is 0

(B) The distance of stopping coal caving is 0.5 times the weighting step

(C) The distance of stopping coal caving is 0.75 times the weighting step

(D) The distance of stopping coal caving is greater than the weighting step

FIGURE 19 Interaction relationship of “main roof-unmined top coal-supports” in an extra-thick coal seam. (A) The distance of stopping coal caving is 0. (B) The distance of stopping coal caving is 0.5 times the weighting step. (C) The distance of stopping coal caving is 0.75 times the weighting cap. (D) The distance of stopping coal caving is greater than the weighting step.

3.5.2 | Distance of stopping coal caving at working face in extra-thick coal seam

According to the numerical simulation and similar simulation test of different stopping coal caving distances in the working face of the 15 m extra-thick coal seam, the movement characteristics of the key blocks above the extra-thick coal seam and the regularity of realizing reasonable distance are obtained, as shown in Figure 20.

For the medium-thick and thick coal seams mined by comprehensive mechanized top coal caving, according to the field experience and the research of relevant scholars, when the working face stops mining, the safe and smooth mining can be realized when the distance is close to or greater than 0.5 times of the key block length (i.e., periodic weighting distance). However, according to the research results of this paper, the supports cannot be safely retracted under this distance of extra-thick coal seam because the mining of extra-thick coal seam gives a large rotary sinking space for key blocks. It is known that for the working face studied in this paper, the thickness of the coal seam is 15 m, the thickness of the immediate roof is 7.95 m, the thickness of the main roof is 13.95 m, and the length of the key block is about 19.5 m. Based on the calculation formula of key block rotation angle\(^{18}\):

\[
\theta = \arcsin \left( \frac{(L_m + L_z) - K_p \cdot L_z}{L} \right),
\]

where \(\theta\) is the rotation angle of the key block, °; \(L\) is the length of the key block, m; \(L_m\) and \(L_z\) are the thickness of coal seam and immediate roof, respectively, m; \(K_p\) is the dilatancy coefficient of rock, 1.4. The rotation angle of the key block of this extra-thick coal seam can reach 37°. If only the thickness of the coal seam is changed to 3.5 m (medium-thick coal seam) and 8 m (thick coal seam), the rotation angle is 1° and 14°, which is reduced by 97% and 62%, respectively. In this case, the distance selection method originally applicable to thick
coal seams is no longer appropriate for extra-thick coal seams. According to the numerical simulation and similar simulation results of different distances of stopping coal caving, for the mining of 15 m extra-thick coal seam, its key block presents a "step shape". When the distance is shorter than the length of the key block, there is still a large space above the rear part of the untapped top coal. Thus, the rotation of the key block on the upper part drives the key block on the backside to intensify the sinking and squeeze the unmined top coal so that the broken main roof rock block and the unmined top coal are pressed into the support, which is not conducive to supports' withdrawal.

To sum up, the distance of stopping coal caving at the working face of 15 m extra-thick coal seam should be greater than the length of key blocks (i.e., more significant than the periodic weighting step distance of the working face). Besides, the distance is too large, its function is not improved, and coal is wasted. The distance of stopping coal caving at the working face studied in this paper is 20 m. In addition, when the working face stops mining, the fracture line of the main roof shall be controlled behind the supports. Therefore, the overall overburden structure can ensure the best stability of the LSRSP.

4 | SUPPORTING OF LSRSP IN FULLY MECHANIZED CAVING FACE OF EXTRA-THICK COAL SEAM

After mastering the reasonable distance of stopping top coal caving before stopping mining in the working face of the extra-thick coal seam, LSRSP can ensure the stability of the overburden structure and then put forward the support scheme.

4.1 | Supports evacuation technology of fully mechanized caving face in extra-thick coal seam

First, it is necessary to analyze the supports' removal process when the working face stops mining, as shown in Figure 21. When stopping mining, the supports of the working face is evacuated in sequence from one side to the other side. After the supports are evacuated, wooden cribbing support is used to undertake the sinking roof. The supports' removal operation is carried out under the protection of two shield supports. With the withdrawal of the supports, the shield supports move forward, and the rear roof will collapse naturally. According to its
technological process, it can be obviously obtained that it is essential to ensure the stable support of LSRSP in front of the supports' removal operation space, so it is imperative to design the support scheme of large section space for stopping mining in the extra-thick coal seam.

4.2 Subzone and graded differential support for LSRSP of extra-thick coal seam

LSRSP comprises the supports area and retracement channel area, as shown in Figure 22.

For the supports' area, it is mainly the roof's support. From its withdrawal process, it can be seen that the roof support in the supports' area should not be too strong. Otherwise, it will cause a significant place on the suspended roof, which will make the subsequent supports bear too much pressure and make it difficult to withdraw. The roof and sides need to be supported for the retracement channel area. The roof needs to be stable in the support removal and front of the operation area. This area will also be disturbed by the supports' removal operation, so strong support means are needed. According to the simulation research, the high-stress area gradually shifts from the deep part to the outer coal rib. It is necessary to prevent the coal body collapse caused by support removal disturbance.

According to the above analysis, the LSRSP's roof and sides are divided into five zones.

Zone I: this zone is supported by the support column. After removing the supports, this zone should sink slowly without roof suspension, so the support strength is the weakest. Based on the above drilling peep and mining support materials, the 4.3 m high-strength anchor cable is selected to support the multi-cracks area of top coal.

Zone II: this zone is supported by the top and front detection beams. After removing the support, this zone needs to limit large deformation, so the support strength must be strengthened. 7.3 m high-strength anchor cable is selected to anchor to the complete area of the top coal to realize all anchoring of the fractured coal body.

Zone III: this zone is the roof of the retracement channel without passive support, which is the key zone to strengthen the support. Maintaining the stability of the whole process of the roof is the basis for the safe retraction of the support. Considering the extra-thick top coal seam of 11.1 m, the combined support of three enhanced support means is adopted: (1) deep hole anchorage: 10.3 m high-strength anchor cable is used to realize the deep anchorage of the whole layer of coal; (2) shallow strengthening: the shallow surrounding rock is strengthened by dense high-strength resin bolts. The bolts and anchor cables are staggered horizontally and vertically to maximize the roof control area; (3) combined anchor cable: the combined anchor cable with robust roof control and anchoring function is used for local reinforcement to consolidate the combined support system.

Zone IV: this zone is the top angle of the retracement channel, which is a critical zone to realize the connection
between the roof and rib support. The support control is carried out according to the angle of 15°, 45°, and 75°; that is, the roof anchor cable is inclined to the side by 15°, and the anchor cable and side bolt are set along 45° and inclined upward by 15°.

**Zone V:** this zone is the sidewall coal rib of the retracement channel. According to the above research results, 2.5 m high-strength dense bolts are used to strengthen the sidewall. At the same time, dense single hydraulic props are used to fix the sidewall and control the roof to limit the coal caving and spalling to the greatest extent.

Finally, the overall polyurethane mesh is used for the comprehensive support of the LSRSP surface layer to realize the connectivity of the above five support zones and give full play to the integrity of the support. The integral polyurethane network realizes one network for the whole roadway, with better continuity and good wrapping of the locally broken coal body, and it emphasizes the joint control. These constitute the “control zoning—strength classification” differentiated support scheme of the LSRSP in the extra-thick coal seam, as shown in Figure 22.

### 4.3 Establishment and analysis of supporting prestress field

To verify and correct the relevant parameters of the supporting scheme, numerical simulation software is
used to simulate the prestressed field of the supportive system in equal proportion, as shown in Figure 23.

The prestressed field realizes the strength classification of the five supporting zones through comparison and verification, and the supportive differences are apparent. At the same time, according to the three-dimensional equipotential surface of the prestressed field, the prestressed connection integrity of the support in the five zones is better, and the top corner support of the retracement channel realizes the connection of the prestressed field between the rib and the roof. By comparing the regular anchor cable support section, the combined anchor cable support section, and the combined support section, it can be concluded that the prestressed concentration area of the joint support in the retracement channel is 3.4 times as deep as that of the standard anchor cable. The combined anchor cable makes the roof in the retracement channel under the muscular support stress within 1.6 m depth, showing a good support effect.

5 | IMPLEMENTATION EFFECT OF FIELD APPLICATION

The LSRSP of the extra-thick coal seam is supported on the spot, and the supporting effect is evaluated by on-site investigation and monitoring, as shown in Figure 24.

On-site support construction is smooth. Under this support, the LSRSP section of the extra-thick coal seam in the early stage of supports’ removal keeps a good molding degree, and the integrity of polyurethane mesh is good, without local tearing. According to the monitoring data of the displacement of the roof and rib area in the retracement channel, the withdrawal operation triggered the removal of the over-front section to grow faster, and the sinkage of the roof was controlled within 200 mm during the whole process, which was conducive to the efficient withdrawal of the supports. From the implementation of support to the withdrawal of all supports for about 30 days, the retracement channel roof did not have a large area of subsidence, rib bulging, or other strong mining pressure phenomenon. This shows
that the overall effect of LSRSP zoning and classification differential support in the extra-thick coal seam is better, and the supports can be evacuated safely and smoothly.

6 | CONCLUSIONS

(1) With the increase of stopping coal caving distance, the range of the medium and low displacement zone of the LSRSP overburden gradually expands; the scope and intensity of the high-stress area of the overlying rock in front gradually decrease and shift from deep to the outside, while the peak stress area shifts from the top coal area to the coal rib of the retracement channel; the depth of the plastic zone of the surrounding rock gradually decreases, and when the distance is greater than 20 m, the top coal begins to appear as an apparent unplasticized area.

(2) When stopping mining in the working face of the extra-thick coal seam, the main roof fracture line should be controlled at the back of supports. When the fracture line of the main roof is in front of or above supports, the overlying rock’s high displacement range, stress concentration strength, top coal sinking degree, top coal plasticization condition, and other indicators are inferior. In similar simulations, the supports under the stable cantilever structure can be moved out smoothly only when the fracture line is at the rear.

(3) The “main roof–unmined top coal–supports” interaction relationship is proposed. The analysis shows that the supports bear more impact and intense pressure from the slipping fundamental block when the stopping coal caving distance is 0; when this distance is 0−0.75 times of the weighting step (short-distance), the dropped coal body cannot effectively restrict the movement of key blocks. Mutual compression and subsidence occur between key blocks, making the broken coal rock block squeeze into the supports, which is different from the medium-thick and thick coal seam working face. The results show that the stopping coal caving distance of the extra-thick coal seam is slightly larger than the length of the key block (i.e., periodic weighting step) is optimal in all indexes.
(4) According to the results of peeping in LSRSP's top coal and simulation of the extra-thick coal seam, the differentiated support scheme of “control zoning—strength grading” is proposed. The scheme is modified and verified by simulating the support prestress field. After field practice, the roof of the retracement channel is better controlled in deformation under the joint horizontal and vertical support, the robust control effect of the combined anchor cable is noticeable, the integrity of the polyurethane network is more substantial, and the working face supports have successfully achieved a safe and rapid evacuation.

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