Study on Reasonable Stopping and Time-Sharing Partition Support of Fully Mechanized Top Coal Caving Face Under the Interference of Stopping Line in Close-Up Coal Seam

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Abstract

Close-distance coal seams are widely distributed in China, and there is a problem of stopping mining in a large number of working faces. Taking Yanzishan mine as the engineering background, the mined-out area and the remaining end-mining coal pillar of No.4 coal seam (upper coal seam) mined in advance caused strong interference to the stopping mining of N316 working face of No.3 coal seam under it. Through field observation, laboratory experiment, and support data collection, the mechanical parameters of coal and rock mass and periodic weighting condition of the working face were mastered, and numerical simulation and similar model experiments were carried out. Three positional relationships between the stopping position of the underlying N316 working face and the upper stopping line were obtained: “externally staggered with the upper stopping line” (ESUL), “overlapped with upper stopping line” (OUL), and “internally staggered with the upper stop line” (ISUL, ISUL-SD for shorter internal staggered distances, ISUL-LD for longer ones). The formation and evolution of the stress arch structure of ESUL → OUL → ISUL-SD → ISUL-LD are obtained from the analysis: ESUL: there is a double stress arch structure of goaf side and end-mining coal pillar side in the overburden and stress superposition appears in the middle arch foot (stopping mining place). OUL: it evolved into a single arch structure of goaf-solid coal, and the stress at the stop of mining was relatively minimum. ISUL-SD: it is still a single arch structure, and the stress at the stop of mining is still small. ISUL-LD: the double stress arch is regenerated and stress superposition occurs at the front arch foot (stopping mining place). At the same time, the morphological evolution process of stress arch is as follows: “front and back stress arches, superimposed with middle arch foot” → “front arch gradually decreases” → “front arch dies, and two arches merge into single arch” → “single arch gradually increases” → “two arches are regenerated, superimposed with front arch foot”. On-the-spot analysis from the combination of stress and overburden structure: ESUL: the stress concentration degree is the highest above the stopping space, and the overburden block in the large-scale caving zone directly acts on the support, which makes the stopping operation difficult. OUL: although the stress environment is the best, the overlying key blocks will have hidden dangers of overall rotation or sliding instability. ISUL-SD: the stress environment is good, and the overlying rock can realize the stable structure of the cantilever plate (the internal staggered distance is less than the periodic weighting step), and the mining is stopped at this position to realize the safe and smooth withdrawal of the support. ISUL-LD: it is basically consistent with stopping mining when single-layer coal is used but is limited by the limited length of the end-mining coal pillar. In addition, the self-digging retracement channel is designed to serve the whole retracement process, and the idea of time-sharing partition support for a large cross-section of mining stoppage and its corresponding scheme is put forward according to the retracement process. Through the simulation of prestressed field and field practice, the roof overlying rock structure is stable during the whole retracement period, thus realizing the safe and smooth mining stoppage and retracement of the working face.

1 Introduction

In the lower coal seam mining of short-distance coal seam groups, the mining condition and the overburdened structure of the upper coal seam will affect its mining (Suo et al. 2013; Liu et al. 2020; Wang et al. 2015). The state of overlying strata of goaf and residual coal body in upper coal seam working face is different, which makes the load and periodic pressure of the support during mining in the lower coal seam working face change dramatically (He et al. 2016; Zhang et al. 2018; Cui et al. 2020). This paper researches the interference of the complex residual coal body in the middle and upper coal seam of the short distance coal seam group, selection of reasonable stopping mining method, determination of position, and design of stopping mining spatial support in lower coal seam working face.

In the entire life cycle of fully comprehensive caving working face, stopping mining and removing supports in a reasonable position is the most important step to end the cycle (Vervoort 2021; Zheng et al. 2019; Lou et al. 2021). Aiming at the difficult problem of mining and reasonable stopping design of the lower coal seam working face disturbed by the upper coal seam, many scholars have conducted extensive and profound research. For coal seam mining under goaf, Pan et al. (2020) think that the roof pressure step distance and advanced support pressure of its working face are less than that of the working face under the non-goaf. Guo and Yang (2021) used UDEC software to analyze the failure height and collapse characteristics of overlying strata in thick coal seam under goaf. Wang et al. (2016) found that the overlying key strata were broken, and the influence range and peak value of abutment pressure decreased significantly only under the influence of interlayer key strata. Liu et al. (2016) used UDEC simulation to get the stress reduction area below the goaf of the upper coal seam, and it is less than half of the original stress. For the selection of stopping mining lines in the working face, Zhu et al. (2021) established a comprehensive evaluation method to determine the reasonable stopping mining line of the working face by using the stress field excited by the seismic wave. Zhou et al. (2017) determined the structure of the reasonable stopping mining line of the working face by using the simulation experiment combined with the PAC acoustic emission instrument. Xue et al. (2014) used numerical simulation to determine the optimal stress environment when the stopping mining line of the working face should be at 115 m away from the pedestrian roadway. For stopping mining design, scholars such as Fei, Li, Lui, and Ma all designed to dig a retracement roadway in front of the working face, and analyzed the deformation mechanism and reinforced support of the roadway (Liu and Zhong 2018; Li et al. 2020; Lv 2014; Ma et al. 2018). Li et al. (2020; 2021) excavated two retracement channels in advance to facilitate rapid transportation and removal of supports, at the same time, a support scheme dealt with the deformation of the surrounding rock of the double channels. For large section coal roadway support, Xie et al. (2020) designed and successfully applied the anchored rock beam bearing structure (ARBBS) based on the support requirements of large section coal roadway. Meng et al. (2020) designed the technical scheme of “three anchors” combined support, which comprises the primary support of full-section anchor net and shotcrete, and the secondary reinforcement of high pre-stressed anchor cable and anchor grouting, according to the characteristics of the relatively broken surrounding rock. Huang and Gao (2013) adopted the combined support scheme of the high-strength bolt, combined anchor cable, W-shaped steel belt, metal mesh, and concrete according to the characteristics of broken top coal in fully mechanized top coal caving mining.

The above scholars have made some achievements in multi-coal seam mining, stop-mining design, and large-section coal roadway support, but the research on the reasonable stop-mining design of lower coal seam affected by the influence caused by complex goaf and coal column distribution of upper coal seam has comprehensively put many factors into consideration, and there are current research gaps. In addition, the stop-mining line design of a single coal seam should not be totally applied to multi-coal seam mining (Zhang et al. 2021; Cheng et al. 2020). At the same time, the traditional advanced extracting retracement channel method has some problems with channel support and risk of rock burst (Lv 2014; Li et al. 2021). Under the strong influence of the close upper stop-mining coal column, the stop-mining and abandonment of working face in lower seam uses this method.

In summary, based on the geological conditions of the close-range double-thick coal seam group mining in Yanzishan mine, the reasonable stop-mining design of the N316 comprehensive mining surface of the coal seam is explored. Through laboratory experiments, field observation, and hydraulic support pressure data to find the coal and rock mechanics parameters, three-dimensional correspondence between the upper and lower coal seams, and the periodic weighting of working face. And through the condition of the cladding and stop-mining requirements, it is considered that the core issues should focus on the above-covered thick coal seam stop coal column to the underlying working face reasonable stop mining position selection. Through theoretical analysis, numerical simulation, and similar ratio experimental simulation, the stress distribution and the migration of overlay rock under different stop-mining positions are obtained, the stress arch structure evolution process is concluded to explain the stress distribution of each stop-mining position, and then through comparing to analyze reasonable stop-mining position under certain condition, and the site rationality analysis and the design of the parking time are conducted combined with the characteristics of field integrated mining, finally we get a set of the reasonable location design process of close-range coal seam working face stop-mining line. At the same time, considering the many shortcomings of the advanced extracting retracement channel method, the design working face is pushed to the stop-extraction line to continue to push out the realization of the self-excavation retracement channel. According to the withdrawal process and time, we put forward a new idea of separated time and separated space supporting when stopping mining large section space, combined with the supporting design of advanced enhancement, follow-up in withdrawal period and post-weakening, and we carry out simulation verification of the pre-stress field. After field implementation, the hydraulic support achieved a safe and smooth, and rapid withdrawal, the various stages of support matched perfectly, this provides theoretical guidance and engineering reference of the reasonable stop-mining design for the same kind of geological conditions.

2 Engineering Background

2.1 Geological conditions

Production capacity of Yanzishan mine reached 4.8 million tons per year, the development way of well-field system is a main inclined shaft and auxiliary vertical shaft, mining No. 4 coal seam of Permian Shanxi Formation and No. 3 coal seam and No. 5 coal seam of Carboniferous Taiyuan Formation at +1035 m, +885 m, and +825 m levels, low gas content in coal seam, the coal mining technology is fully mechanized top coal caving. As shown in Fig. 1, the depth of N316 working face in No. 3 coal seam is about 400 m, the strike length is 2517 m, the dip length is 180 m and the dip angle is 2°. The average thickness of the coal seam is 5.30 m, the mechanical mining height is 3.2 m, and the coal caving height is 2.1 m. The upper 25 m is the N416 and N418 goaf of No. 4 coal seam, which belongs to the mining situation under the goaf of the lower working face of the close coal seam group.

2.2 Working condition

(1) Influence of overlying goaf and end-mining coal pillar

As shown in Figure 2, the N316 working face is now vertically mapped to the overlying coal seam, and it is found that 80% of the area is the mined-out area, and the left end-mining coal pillar is in front of it. The different overburden structures of goaf and end-mining coal pillar in N416 and N418 face will have a direct impact on the stopping of N316 face. From the profile, it can be seen that the mining stopping in different positions of N316 working face corresponds to different overlying rock states, from which three kinds of mining stopping areas are obtained.

□ Area □: stopping mining under the mined-out of N416 and N418 and staggering the upper stopping line externally, referred to as ESUL.

□ Area II: stopping mining in the area below the stopping line of N416 and N418, and overlapping with the upper stopping line, referred to as OUL.

□ Area III: stopping mining under the entity coal of the remaining end-mining coal pillar of No. 4 coal seam and staggering within the upper stopping line, referred to as ISUL.

(2) Selection requirements of stopping coal caving time

To realize reasonable stopping mining in the working face, not only the influence of different stopping mining positions should be considered, but also the movement state of the main roof plate before stopping mining should be considered for timely stopping coal caving. As shown in Figure 3, according to the monitoring of support pressure, it is judged that the last pressure is coming from the established stopping line, and the scraper conveyor can stop coal caving after the pressure starts to evacuate. Then, the working face continues to advance to the key block B of the main roof to complete the sliding rotary movement, that is, after the weighting is finished, the mining and moving frame is stopped under the stable cantilever plate formed by the whole main roof structure.

(3) Requirements of each stage of stopping mining operation

The traditional stopping operation of the working face includes two steps: the selection of stopping position and stopping space support as shown in Fig. 4, reasonable stopping operation should have the following 6 stages and be accompanied by 6 requirements.

Stage a: it is required to preliminarily determine the position of stopping mining where the overlying rock structure is relatively stable according to the coal and rock conditions on the coal seam, in this paper, it is necessary to consider the influence of stopping mining line of overlying No.4 coal seam.

Stage b: to form a reasonable stopping coal caving distance, it is required to determine a reasonable stopping coal caving time according to the movement state of the overlying strata on the working face, stopping coal caving to help support the breaking of the overlying main roof is very important to reduce the supporter pressure during mining.

Stage c: with the moving of the hydraulic support, the laying of metal mesh to support the broken top coal is a key step to ensure the smooth removal of the hydraulic support and control the safe collapse of the roof after the removal of the hydraulic support.

Stage d: the withdrawal support channel and support together form a large section space for stopping mining. It is required to effectively support the roof and coal wall of the withdrawal support channel to prevent the fall of ground and spalling rib accidents in the withdrawal support channel.

Stage e: during the hydraulic support removal step by step, prevent large-area roof collapse of the whole stopping mining space from causing hydraulic support pressing and roof accidents, and it is required to follow the hydraulic support removal operation to cover and remove the hydraulic support.

Stage f: after the support is withdrawn, prevent the roof of the evacuated support area from sinking excessively and crushing the support, making it difficult to remove the next support, it is required to move the support and coal caving in turn until the withdrawal is completed.

3 Experiment And Observation

To realize the reasonable stopping design of the working face, it is necessary to master the periodic weighting step distance, weighting intensity, top coal crack development, and mechanical characteristics of coal and rock.

3.1 Measurement of coal mechanical parameters in N316 working face

To rationally design the support means of large cross-section space at the stopping mining position, the rock mechanics parameters of the coal in No.3 coal seam N316 working face are measured to master the coal quality status of the coal seam. For this reason, drilling core was carried out in the roadway on both sides of N316 working face and brought back to the laboratory to make standard rock samples, and density test, uniaxial compression test, and shear splitting test were carried out respectively. As shown in figure 5, the experimental data are averaged to get the parameters shown in Table 1 below.

Table 1
Parameters of coal samples for indoor test

Parameter	Density test	Uniaxial compression experiment			Split tensile test	Shear test	
	Natural drying density ($g \cdot cm^{-3}$)	Uniaxial compressive strength (MPa)	Elastic modulus (Gpa)	Poisson's ratio	Tensile strength (MPa)	Cohesion (MPa)	Internal friction angle (°)
Numerical value	13.31	14.24	4.48	0.295	1.02	3.88	37.32

3.2 Borehole observation on surrounding rock condition of roof of N316 working face

To study the support of large cross-section space top coal in the later period, the development of cracks in top coal above the support in normal mining face is designed to be peeped by drilling holes, as shown in Figure 6 below.

Through the borehole peep at the depth of 3 m in front of the support, it is found that there are many cracks in the coal body of the roof, the whole of the top coal is broken, and the rock part is relatively complete.

The crushing condition of the top coal is different in different measuring positions, for example, the peep view near the No. 30 hydraulic support shows a large number of broken belts concentrated in the middle of the top coal, and it is speculated that there may be large transverse fractures here; the peep view at No. 70 support shows that the shallow coal seam has been broken in a large scale, and with many open cracks, the coal block is easy to fall; the peep view at No. 110 support shows that the top coal is soft, there are many broken coal and collapse holes at the boundary of roof coal and rock, and there are many cracks in the rock mass. Comprehensive observation shows that the fractured zone of the roof is more than 2 m, and there is the possibility that the whole top coal will fall off in a local area, so it is difficult for bolt support to play an effective role.

3.3 Observation of periodic weighting law in N316 working face

By detailed observation of the data on the pressure of each support during roof pressurization, found that N316 working face support pressure increase phenomenon is obvious. As shown in Table 2 below, 30.3% of the hydraulic support pressure directly exceeded the limit, causing damage to the support, and 65.6%

of the hydraulic support was at medium or above weighting strength, it can be seen that the periodic pressure caused by the movement of the periodic fracture of the main roof makes the mining pressure of the working face appear more intense.

Table 2
Support pressure condition during weighting

Object	Type	Quantity	Proportion
The support pressure exceeds the limit	Front column overrun and back column overrun	3~9	2.5%~7.4%
	Front column overrun	24~37	19.7%~30.3%
	Back column overrun	3~10	2.5%~8.2%
Roof pressurized range of support	Basically no roof pressurized	0~10	0~8.2%
	Small-area roof pressurized	15~25	12.3%~20.5%
	Medium-area roof pressurized	15~30	12.3%~24.6%
	Large-area roof pressurized	30~50	24.6%~41.0%

As shown in Table 3, the basic parameters of N316 working face periodic pressure are obtained by statistical analysis after the support pressure data is collected during several weighting periods following the advancing of the working face. The periodic pressure step distance of N316 face in No. 3 coal seam is 17~26 m, according to the duration of mining and the number of cutters, the time of laying metal mesh and supporting support roof can be judged, which is described in the following text.

Table 3
Parameters of periodic pressure in working face

Type	Statistics of pressing step distance /m	Duration and distance of roof pressurized	Duration and distance of no roof pressurized	The average load of support under large-area roof pressurized
Parameter	17~26 m	About 1 day, 2~6 m	3~5days, 14~24 m	About 25~28 MPa
Remark	Average 21.5 m	Cut 3~7 knives of coal	Cut 18~30 knives of coal	The statistical average of multiple roof pressurized

4 Theoretical And Simulation Analysis

To determine the reasonable stop-mining position of the lower coal seam in the close distance coal seam under the influence of the overlying end-mining coal pillar, theoretically analyze the three basic position relationships of stopping mining in the close distance coal seam, and the suitable stopping position is determined by numerical simulation, similar simulation, and field practice.

4.1 Interaction of overlying strata at different stopping positions

As shown in figure 7 above, the characteristics of the three basic stopping positions and the interaction of their main roof key blocks in the N316 face are analyzed as follows:

□ ESUL: the main roof of the upper coal seam has been broken and the goaf has been compacted. When mining the lower coal seam, the main roof of the lower coal seam is broken periodically, which makes the main roof of the upper coal seam prone to secondary breaking and then turning and sinking, and its weight is all acting on the key blocks of the lower coal seam. When mining is stopped at this time, the support may directly bear the pressure of the basic top key blocks of the upper two layers of coal.

□ OUL: the key block of the main roof of the upper coal seam has a secondary rotation and the rotation angle reaches the maximum, part of the force squeezes the C' block laterally, and the goaf is compacted with the key block of the lower coal seam, and the support does not act as the main body of the load.

□ ISUL: the upper coal seam plays a certain bearing role, and the fracture of the overlying rock structure is consistent with the mining of the normal working face. At this time, the main roof of the upper coal seam belongs to a key layer overlying the working face of the lower coal seam, and its key block generally lags behind the fracture of the key block of the main roof and rotates and extrudes the backside of the key block of the main roof.

4.2 Numerical simulation and analysis of stopping mining in short-distance coal face

(1) Establishment of numerical model

In order to analyze the fracture pattern and stress field distribution of overlying strata at different stopping positions, the discrete element numerical simulation method is used to construct a calculation model with the same size as the actual size in the field, and the hydraulic support model of the N316 working face is constructed at the same rate, as shown in Figure 8. The size of the model is 250 m × 88.1 m, and the vertical stress of 8.5 MPa and the horizontal gradient stress of 10.2 MPa ~ 12.4 MPa is applied to the boundary. The No. 4 coal seam in the model is first mined to the preset stopping mining line, and then the lower coal seam is mined. Near the stopping mining line of the upper coal seam, different fracture line locations of the main roof may affect the simulation results when mining in the lower coal seam. The following three fracture line positions are preset for simulation to grasp the numerical calculation results of different stopping mining positions under different fracture positions of the main roof.

(2) Formation of stress arch and stress superposition of arch foot

As shown in Figure 9, through numerical simulation, it is found that in the process of crossing the stop mining line from below the goaf to below the entity coal, an obvious stress arch structure will be produced and will evolve accordingly. The evolution characteristics of arch stress at different stopping positions are as follows:

① When the stop position is staggered at the upper stop line 50 m externally, the stress arch structure occurs on the side of the rear goaf and at the front upper stop line, and the two arch feet are superimposed, and the superposition is located in front and above the working face, at this time, the stress environment is extremely unfavorable to the stopping operation.

② With the shortening of the staggering distance, the stress arch on the side of the upper stop coal mining pillar becomes smaller and the rear arch becomes larger, but the superposition strength of the two arch feet is still strong.

③ When the stopping position overlaps with the upper stopping line, the front arch dies and the goaf-solid coal single-arch structure is formed, and the concentration degree of leading abutment pressure in the working face is the lowest.

④ When the stop position is in the internal staggered stopping line until the structure of the overlying strata above the working face begins to break, the stress is concentrated in the front arch foot.

⑤ With the gradual increase of the internal staggering distance, the single-arch structure has re-evolved into a double-arch structure, the difference is that the stress of the double-arch structure is superimposed on the front arch foot, and the front arch foot is in front and above the working face, so the stress environment is not conducive to mining stopping operation.

(3) Analysis of stress of each stopping mining position under different prefabricated fault lines

To show the stress status of different fault lines and stopping mining positions in detail, three indexes of vertical stress, maximum shear stress, and the second invariant deviatoric stress are introduced to show the stope stress environment (Zhang et al. 2014; Wang et al. 2021; Chen et al. 2020). According to the numerical calculation results shown in Fig. 10, the following features can be observed:

① From the comparison of the programs of the three stress indexes at the same stopping mining position but different fault lines, it can be obtained that the fault line positions have no apparent influence on the overall stress shape, location, and peak value, but there is only a tiny difference in the degree of stress concentration, which is the same in general.

② Stopping mining at an external-staggered distance of 50 m from the stopping mining line, the programs of the three indexes show the superposition of stress arch foot, the vertical stress, shear stress, and J_2 of the coal wall in front of the retracement channel all exhibit the characteristics of high depth, and the longitudinal depth is more than 30 m, where J_2 peak value belt is tilted to the gob side obviously, therefore, it can be concluded that the continuity and high value of longitudinal stress transfer caused by stopping mining under goaf, which is extraordinarily unfavorable for stopping mining operation.

▯ Stopping mining directly below the upper stopping mining line, the programs of the three indexes all show a stress arch, and the whole stress environment is optimal; the stress concentration of the coal wall in front of the retracement channel is relatively low, and there is no vertical development. It is suitable for stopping mining in terms of stress.

▯ Stopping mining at an internal-staggered distance of 50 m from the stopping mining line, the programs of the three indexes show the double stress arch superimposed on the front arch foot, and the stress superposition of the front arch foot is apparent, the vertical stress concentration area of the coal wall in front of the retracement channel has a large transverse width, the local concentration of shear stress, and longitudinal solid connection. While J_2 has both characteristics, both the transverse and longitudinal directions show relatively strong peak belts, which is also unfavorable for stopping mining operations.

(4) Analysis of reasonable stopping mining position based on numerical simulation

The above analysis shows that stopping mining at the position of stopping mining line on the overlap in the working face below has a relatively good stress environment. An elaborate simulation is made to explore the best stopping mining position, as shown in Fig. 11, it is summarized as the following characteristics:

▯ This area is in the process from external-staggered to overlap and then to internal-staggered, vertical stress, shear stress, and J_2 all show the phenomenon of arch foot superposition, front arch extinction, and single arch formation of double stress arch.

▯ Three indexes comprehensively compare the environment of stress, it is the best stopping mining position of stress angle that the position overlaps the upper stopping mining line and the internal-staggered upper stop line by 10 meters, and the stress concentration is the lowest.

▯ As shown in the figure above, once the internal-staggered distance is too large, secondary stress concentration occurs at the front arch foot of the stress arch, which is caused by the breakage of the cantilever structure; thus, a proper stopping mining position can be obtained to avoid the internal-staggered upper stopping mining line within a long distance, it should be in the interval from overlapping to short-distance internal-staggered.

4.3 Similar simulation of stopping mining in lower coal seam working face

A similar ratio model of 1: 120 in a laboratory large two-dimensional similar simulation platform is established to verify the rationality of theoretical and numerical simulation analysis. The model is excavated from left to right, and the left boundary prefabricates the empty side to achieve the main roof rotating and sinking. The model first excavates No.4 coal seam and then excavates No.3 coal seam below after reaching the designed stopping mining line.

As shown in Fig. 12, through similar simulation experiments, the following rules are obtained:

 Figs. (a) and (b) show the mining and stopping mining stages of overlying No.4 coal seam. There is no coal caving within the step of periodic pressure in one cycle in the stopping mining stage.

 Excavation of No.3 coal seam from Fig (c), its main roof fracture line can be observed in front of the hydraulic support, secondary breakage occurred in the main roof of the upper coal seam, and then slide and sink with the main roof of lower coal seam simultaneously, which acting on the support.

 Figs. (d) and (e) show the internal-staggered and overlapping upper stopping mining line in the retracement channel. When the lower stopping mining line is on the external-staggered side, the main roof fracture line is located in front of the support, and the supports are compacted by whole high depth broke rock formation so as to they are not suitable to stay here for a long time and remove; when the upper stopping mining line is overlapped, the rock formation behind the support of the working face is integrity broking, and the goaf is compacted, while the supports are just standing below the cantilevered structure and protected by it.

 Figs. (f) to (h) show that the retracement channel is gradually internal-staggered on the lower stopping mining line. When the internal-staggered distance is small, the main roof fracture line is above the support. However, the area without coal caving plays a bearing role in breaking the main roof to a certain extent and slows down the support pressure, as well as the overburden structure above the solid coal is still stable; with the gradual deepening of the internal-staggered distance, the overburden structure above the support began to break, the main roof breaking of the upper coal seam is caused by the lower, and then to the fracture of the large structure of the whole high-depth overlying rock. The fracture lines are all above the support, so the support should not stay for a long time and remove.

4.4 Comprehensive simulation and on-site selection of actual stopping mining position

The above simulation shows that overlapping and short-distance internal-staggered are suitable for stopping mining in stress fields and overburden structures. However, according to field experience, when the stopping mining lines are overlapped, there is a hidden danger that the key blocks on the working face will slide instability as a whole. Therefore, the actual stopping mining position is selected as the internal-staggered stopping mining line within a short distance, the detailed selection process of parking and stopping location is shown in Fig. 13. The purpose of the process design is to make the stopping position avoid the pressure interval and have a short-distance internal-staggered on the lower stopping mining line so that the support can be removed safely and smoothly under the optimal stress environment. Furthermore, the distance of stopping coal caving is generally larger than the average periodic weighting step. On the one hand, it can bear the main roof of breaking and sinking; on the other hand, it is convenient to lay the metal mesh in advance to facilitate the initial strengthening support of the roof.

5 Design Of Large Cross-sectional Space Support At The Stopping Place

On the basis of selecting the actual stopping position, the supporting design of stopping mining in large space is carried out. Because the support design should serve the withdrawal process, it is not appropriate to apply traditional supporting thought to design schemes. Instead, reasonable design should be carried out under the new supporting thought which serves the withdrawal process and considers the time effect.

5.1 Support design principle based on support withdrawal technology

Reasonable support design can guarantee the operation requirements of each stage on site. The process flow of the hydraulic support withdrawal process is shown in Figure 14. Through the fine division of the support required by the sequential frame dismantling process in each stage, the key points of support in three periods are put forward:

 In the early stage: the purpose is to support of large span space after stopping mining and prevent the roof of 8.68 m span from falling partially and integrally. This emphasis is on the control of overlying broken top coal in the retracement channel, and the support at this stage should combine strength with weakness to avoid over-strong support of the roof above the support.

 During the withdrawal period: the purpose is to dynamically follow the supporting working space and to ensure the stability of the roof of the dismantling working position and passageway. Especially, since the personnel are concentrated in the area where the racks are being withdrawn, it is necessary to set up shield supports to cover the whole operation and prevent the racks from being withdrawn in advance.

 At the later stage: the purpose is to lap the fallen roof coal after the support is withdrawn, so as to prevent the top coal from falling directly and crushing the adjacent support. At the same time, it is necessary to prevent the suspended top coal from falling, so as to prevent the large-area top coal from suddenly falling and causing strong dynamic pressure disaster.

5.2 Time-sharing partition support technology for the roof of mining-stopped space

According to the withdrawal support cycle of about 35 days and the different key points of each period of the dismantling process, the idea of time-sharing partition support for the roof in the stop mining space is put forward, and its principle is shown in Figure 15. Under the guidance of this supporting thought, the mining-stopped space is no longer supported by roof reinforcement alone but is designed according to the needs in accordance with the support emphasis of the dismantling process in different operation periods. Here, in order to meet the requirements of ground control in a specific operation period, it is impossible to support the roof too strongly, which leads to the consumption of consumables and large-area suspended roof, so that it cannot be put down in the later period, and it is impossible to support the roof too weakly, which leads to the roof caving accident in the early period and the frame withdrawal period. Therefore, the reasonable spatial support for stopping mining is the merger of strength and weakness, and the time effect is obvious, which meets the requirements of ground control in every stage of the withdrawal process.

5.3 Analysis of key factors of support in mining-stopped space

Under the guiding ideology of time-sharing partition support for the roof, the key to the support of large section space for stopping mining is to ensure that the stopped mining position is under the stable main roof plate structure, and the other is to reasonably determine the parking position and lay the roof protection net in time. As shown in Figure 16, the foundation of effective support is that the cantilever plate above the stop position has a stable structure. During the whole dismantling process, the roof of the bracket is supported by the early bracket and the later woodpile, and the roof of the passageway is supported by the physical coal gang and the shield bracket during dismantling., both of them require better roof integrity. Therefore, the layout of double-layer metal mesh to achieve strict watch protection, the key to its implementation is to determine the reasonable stopping coal caving position and lay the mesh in time.

5.4 Support parameters and effect of time-sharing partition in stopping space

(1) Design of supporting scheme

The time-sharing partition support scheme designed according to the support withdrawal process is shown in Figure 17.

 Strengthening support in the early stage: all roof is supported by anchor cables, and three anchor cables are laid above the support and the channel respectively. The roof of the channel should be supported with emphasis, but too dense support should not be adopted. Therefore, the combined anchor cable is designed to anchor the roof with local strength, so as to achieve the supporting effect on the basis of reducing consumables. In order to support the middle area of long-span space, a single hydraulic prop is set up to enhance the ability of roof protection. The sidewall of the channel is set with anchor rods to prevent the crushed coal on the surface from extruding out. Double-layer metal mesh is laid on the whole section to effectively prevent the roof from falling. The specific parameters selected by each supporting material are shown in the above figure.

 Follow-up support during withdrawal period: in order to ensure the stability of the roof in the working space for frame removal and protect the safety of workers, the frames are removed from one end of the support group to the other end in turn, and two shield supports are set to support the roof in the whole process.

 Weakening support in the later stage: after withdrawing the bracket, the wooden pallets were staggered in time to undertake the sunken roof, and then the shelves were removed in turn and then continued to be erected. It is worth noting that because the roof above the bracket is anchored by anchor cables, if the roof does not sink but hangs after the bracket is removed, it is necessary to disassemble the support for caving operation, so as to prevent the hanging roof from crushing the bracket to be removed and the accident that the roof suddenly falls in a large area.

(2) Support pre-stress field

As shown in Figure 18, the three-position prestressed field of anchor cable and combined anchor cable support is constructed. By comparing the normal anchor cable support section, combined anchor cable support section, and their combined support section, it can be seen that the stress field of the channel roof is stronger and has good continuity, while the prestressed field of the roof above the bracket is weaker, thus avoiding over-strong support and realizing the strong and weak support of the roof position in the large-section space where mining is stopped. At the same time, the supporting stress of the combined anchor cable is obviously stronger than that of the common anchor cable, and the depth of the supporting high-stress area is about 3.5 times that of the common anchor cable, and the range of the high-stress area combined with the common anchor cable is increased by 2 times, which can achieve better-supporting effect on the basis of saving the number of anchor cables.

(3) Field application effect

Figure 19 shows the whole process from the formation of the stop mining channel to the large cross-section space support and then to the withdrawal of bracket. The hydraulic support in the N316 working face was safely and quickly withdrawn within 35 days. During the whole withdrawal period, it was difficult to anchor in local areas, which was due to the large broken depth of top coal in local areas. In addition, the double-layer metal mesh had an obvious effect on protecting the surface of broken coal in the roof. To sum up, the support scheme designed according to the technology of frame dismantling has realized the effective control of the large-section space roof after stopping mining, with fewer consumables and high safety.

6 Conclusions

In this paper, the N316 working face in the lower coal seam of Yanzishan coal mine is taken as the research object, and the influence of goaf of the upper coal seam, end-mining coal pillar, and entity coal on its reasonable stopping position and the effective support scheme of stopping mining in large cross-section space are studied. Through laboratory experiments, field observation, theoretical analysis, numerical simulation, similar simulation, and practical application, the following conclusions are obtained:

(1) Under the interference of the end-mining coal pillar in the upper coal seam, there are three categories of the positions of stopping mining lines in the lower working face: ESUL, OUL, and ISUL. Combined with similar experiments, the interaction relationship between key blocks in the main roof of two coal seams is analyzed: ① ESUL: the main roof of the upper coal seam is prone to secondary breakage and the main roof of the lower coal seam sinks in rotation, which directly acts on the key blocks of the lower main roof. ② OUL: the key block of the upper coal main roof rotates twice and the rotation angle reaches the maximum, and the stopping position is under the cantilever plate structure. ③ ISUL-SD: the overlying rocks in the upper and lower goaf of coal seam are completely broken and compacted, and the overlying cantilever plate structure at the stop position is still stable. ④ISUL-LD: it is basically consistent with the movement state of overlying strata in single coal seam mining.

(2) According to the discrete element numerical simulation, it can be seen that the process of stopping mining position from ESUL→OUL→ISUL-SD→ISUL-LD is accompanied by the generation and evolution of stress arch structure: ① ESUL: there is a double stress arch structure of goaf side and end-mining coal pillar side in the overburden and stress superposition appears in the middle arch foot (stopping mining place). ② OUL: it evolved into a single arch structure of goaf-solid coal, and the stress at the stop of mining was relatively minimum. ③ ISUL-SD: it is still a single arch structure, and the stress at the stop of mining is still small. ④ ISUL-LD: the double stress arch is regenerated and stress superposition occurs at the front arch foot (stopping mining place). At the same time, the evolution process is refined and verified by introducing vertical stress, shear stress, and second invariant of deviatoric stress, and the morphological evolution process of stress arch is obtained: “front and back stress arches, superimposed with middle arch foot” → “front arch gradually decreases” → “front arch dies, and two arches merge into single arch” → “single arch gradually increases” → “two arches are regenerated, superimposed with front arch foot”.

(3) Comprehensive numerical simulation, similar experiments, and field conditions can be obtained: ① ESUL: the stress concentration degree is the highest above the stopping space, and the overburden block in the large-scale caving zone directly acts on the support, which makes the stopping operation difficult. ② OUL: although the stress environment is the best, the overlying key blocks will have hidden dangers of overall rotation or sliding instability. ③ ISUL-SD: the stress environment is good, and the overlying rock can realize the stable structure of the cantilever plate (the internal staggered distance is less than the periodic weighting step), and the mining is stopped at this position to realize the safe and smooth withdrawal of the support. ④ ISUL-LD: it is basically consistent with stopping mining when single-layer coal is used but is limited by the limited length of the end-mining coal pillar. Among them, it should be ensured that the internal staggered distance is not greater than the periodic weighting step, and at the same time, the distance of stopping coal caving in advance is not less than the periodic weighting step, so the design flow of the actual stopping position for realizing short-distance internal staggered mining is given.

(4) The self-digging retracement channel is designed to serve the whole retracement process. According to the sequential withdrawal process, the time-sharing partition support scheme of large-section space partition at the stopping place is designed. The field practice found that the roof above the support was

protected but not strengthened in the early stage of zoning strengthening support, and the combined anchor cable played an obvious role in the channel roof support, which was in line with the simulation results of supporting prestress field. Follow-up support of shield support during the withdrawal period and weakening support of wood crib in later stage is coordinated in an orderly manner, and sequential withdrawal of the support is fast and efficient. The roof overlying rock structure is stable during the whole withdrawal period, and the mining suspension and withdrawal of the working face are safely completed on schedule.

Declarations

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Conflict of interest The authors declare that they do not have any commercial or associative interest that represents a conflict of interest in connection with the work submitted.

Ethical approval The experiments comply with the current laws of China.

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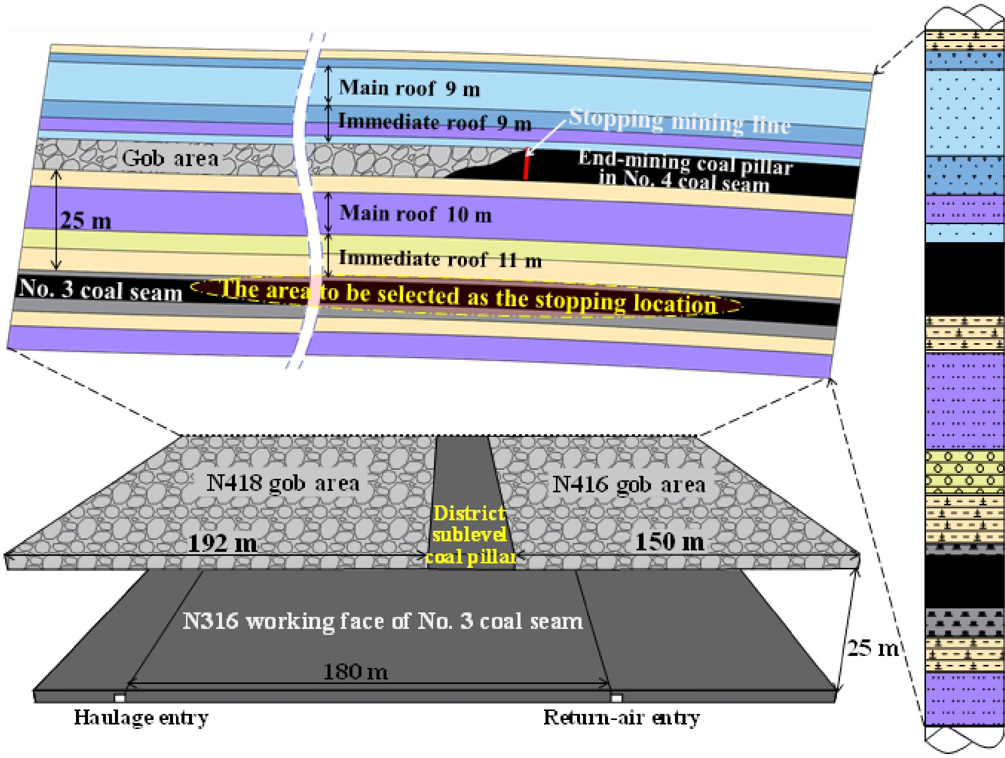
Figures



Rock stratum	Thickness/m
Kaolin rock	2.0
Gritstone	2.0
Siltstone	9.0
Gritstone	4.0
Medium sandstone	3.0
Siltstone	2.0
No. 4 coal seam	7.5
Kaolin rock	4.0
Medium sandstone	10.0
Conglomerate	4.5
Kaolin rock	5.3
Carbonaceous mudstone	1.2
No. 3 coal seam	**5.3**
Carbonaceous mudstone	3.2
Kaolin rock	3.6
Medium sandstone	5.5

Figure 1

Position relationship of short-distance coal seam and coal-rock columnar chart

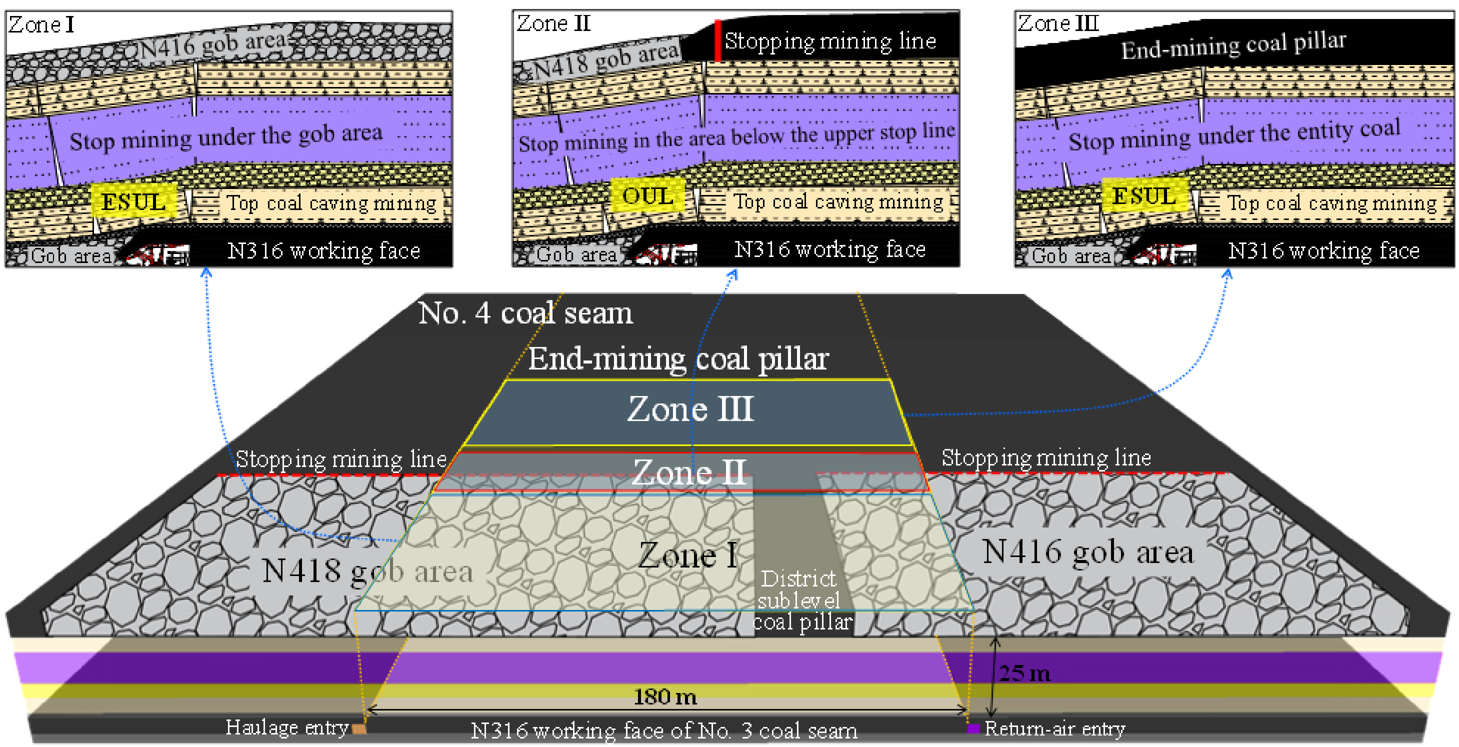


Figure 2

Schematic diagram of overlying coal and rock in N316 working face of No.3 coal seam

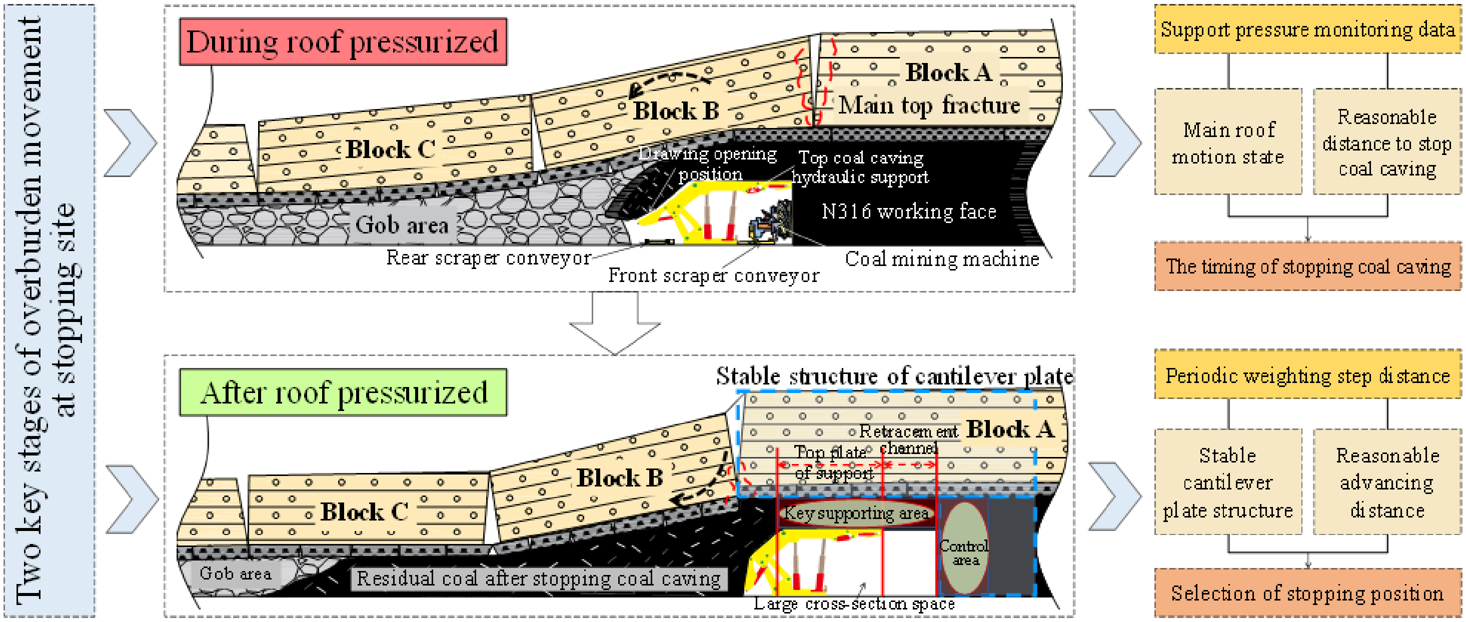


Figure 3

Timing selection fromstopping coal caving to stopping mining

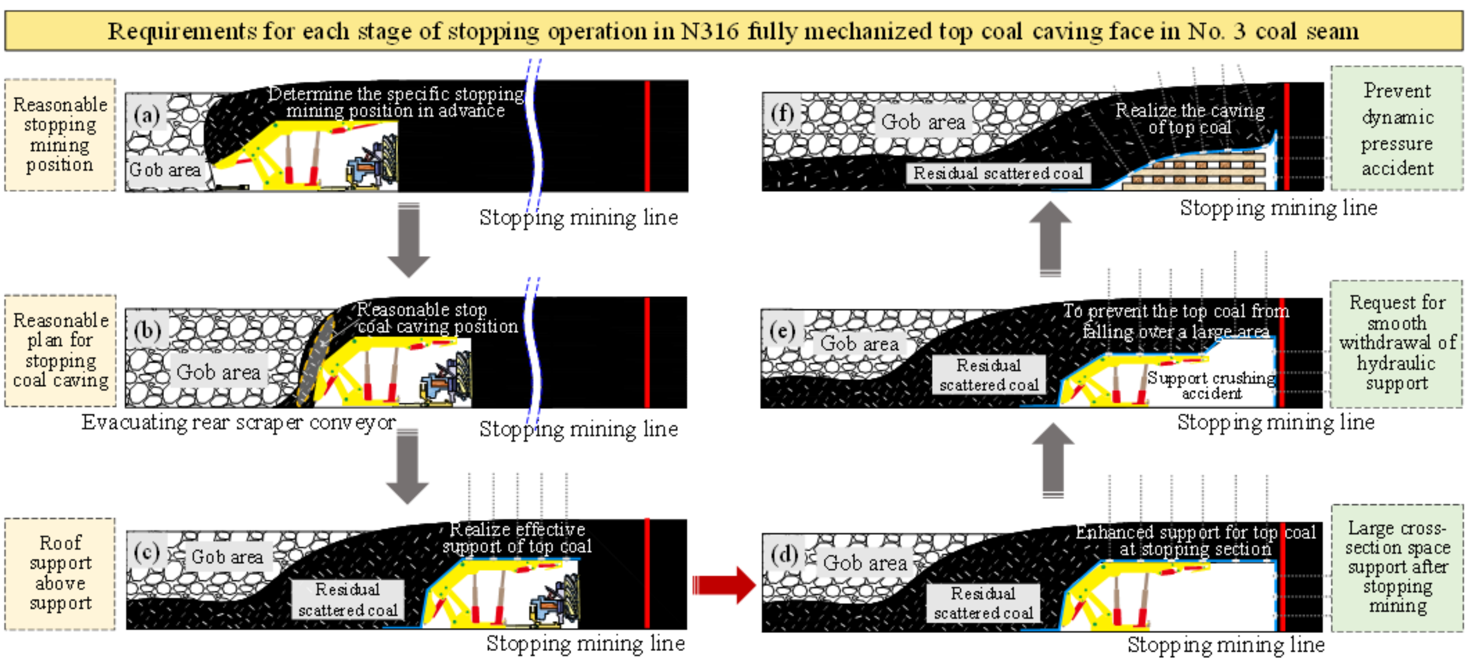


Figure 4

Schematic diagram of requirements for each stage of stopping operation

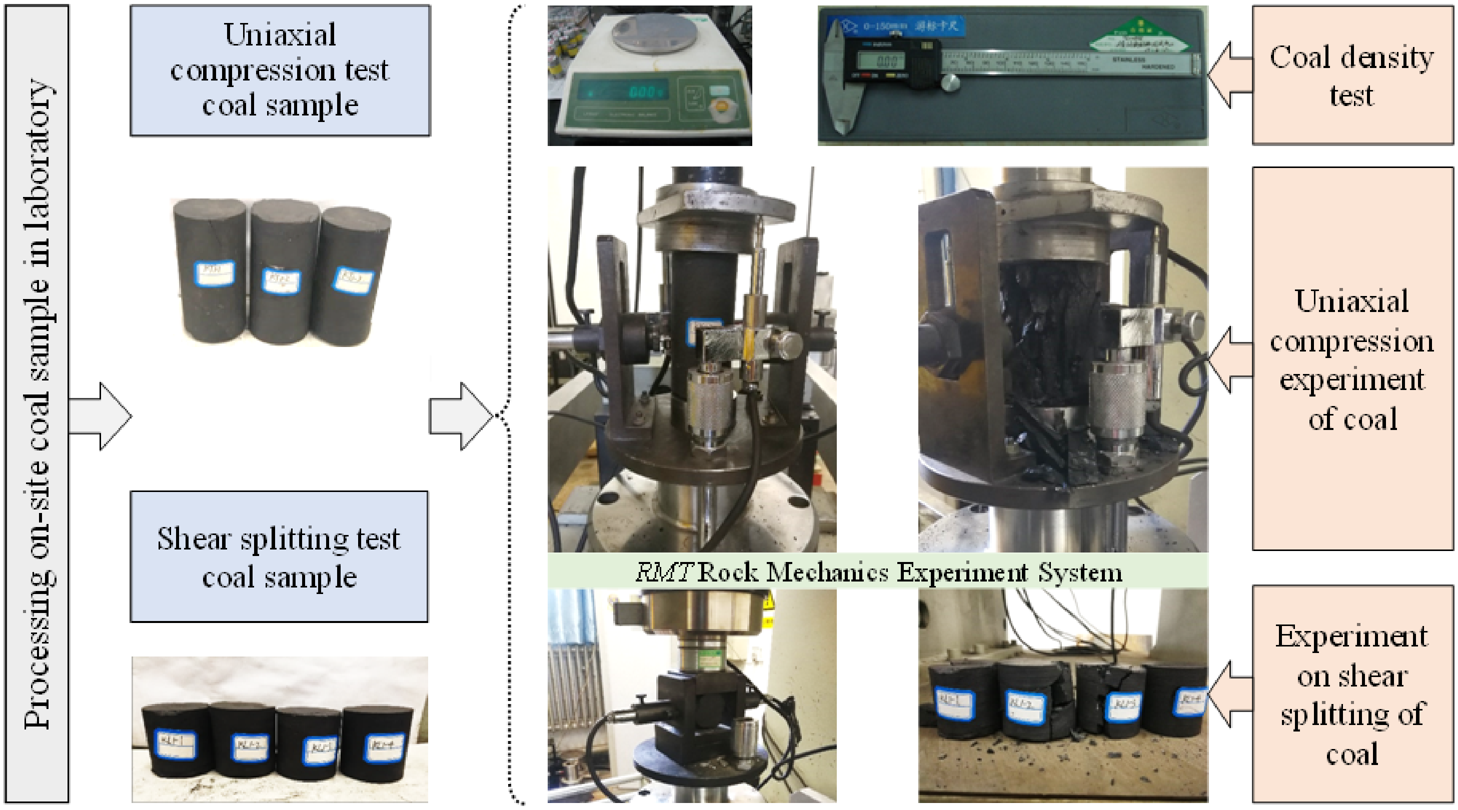


Figure 5

Measurement of parameters in laboratory rock mechanics experiment

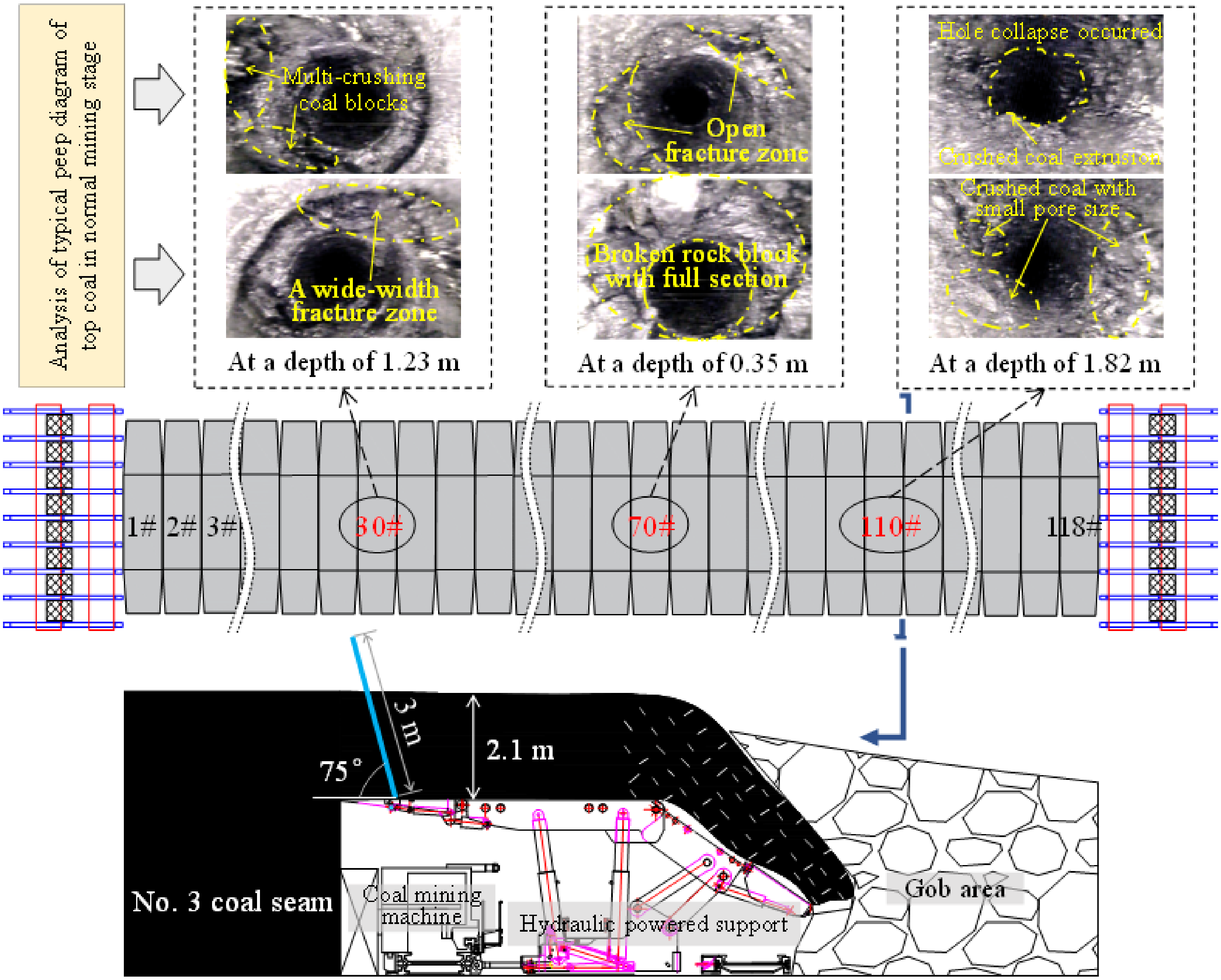


Figure 6

Location and peep view of boreholes arranged on site

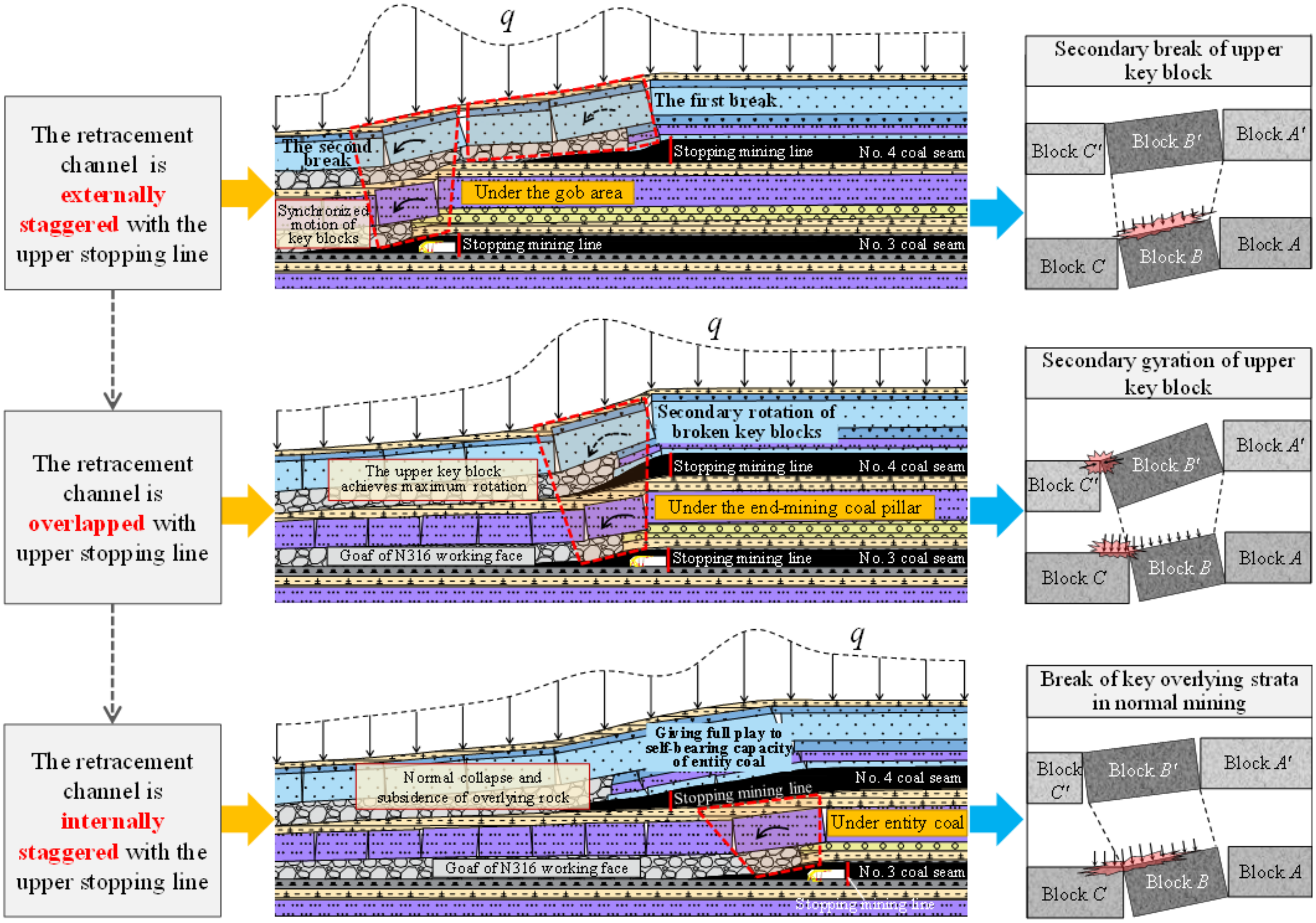


Figure 7

Interaction between key blocks under different stopping positions

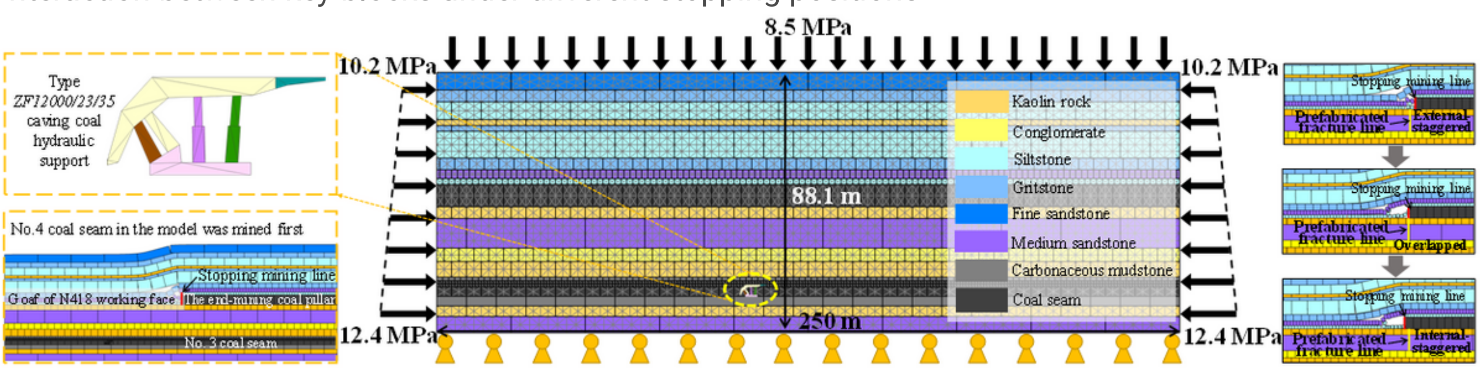


Figure 8

Schematic diagram of the numerical model

Figure 9

Simulation diagram of stress arch evolution

Figure 10

Stress program under different fault lines and different stopping positions

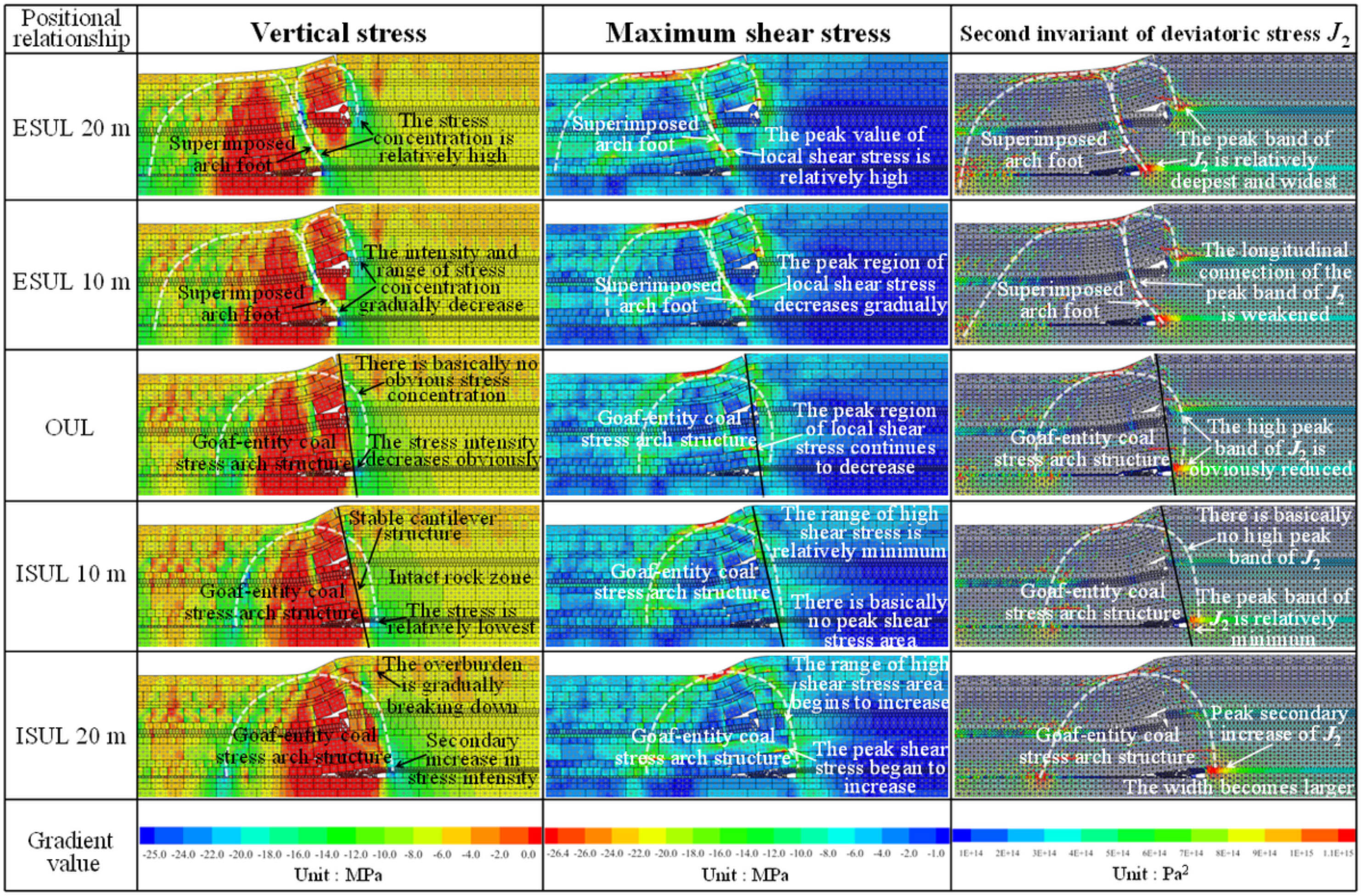


Figure 11

Fine simulated stress contrast program of the area under the upper stop line

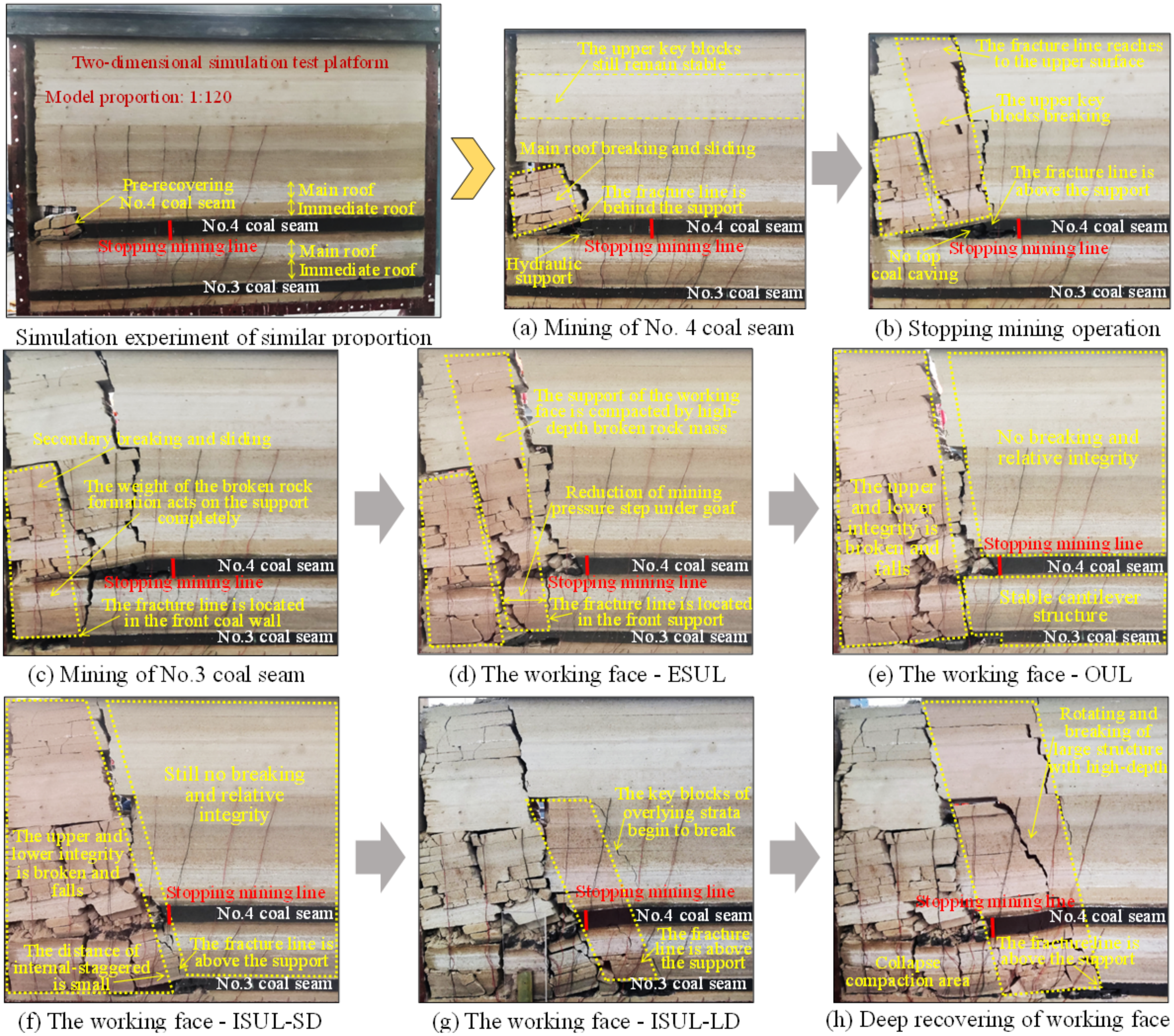


Figure 12

Similar simulation experimental diagram of different stopping positions

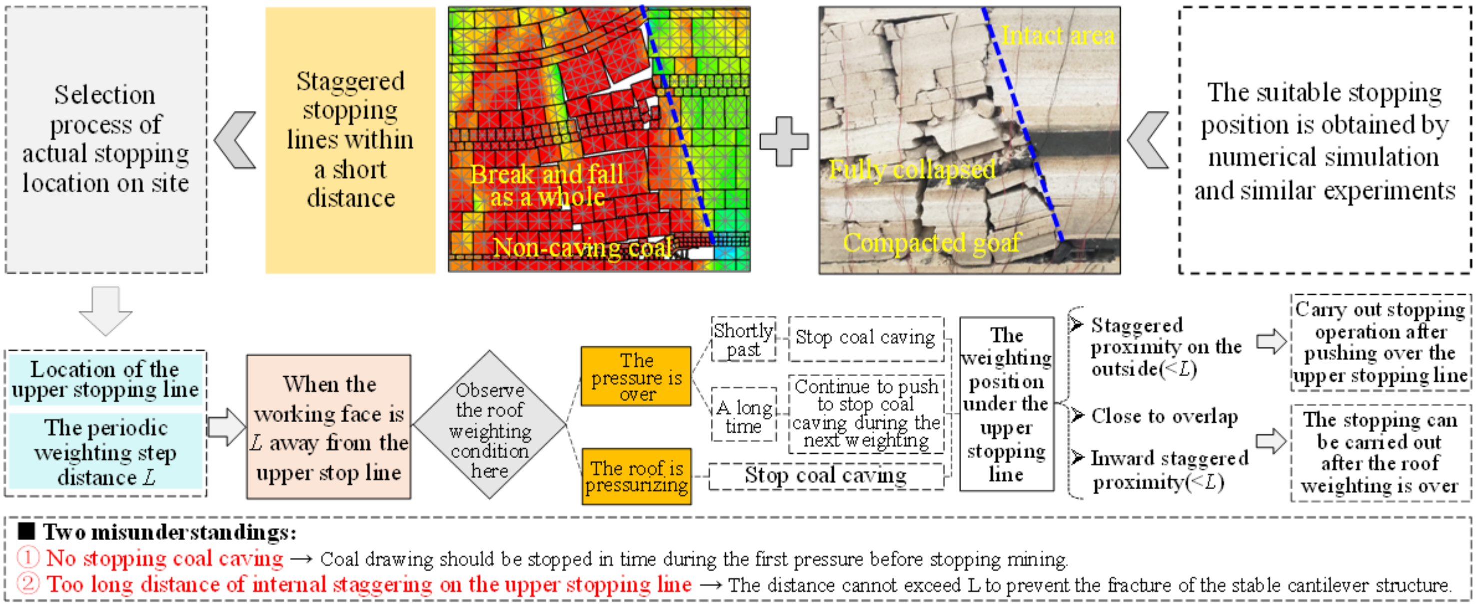


Figure 13

Flow chart of comprehensive simulation and site stop location selection

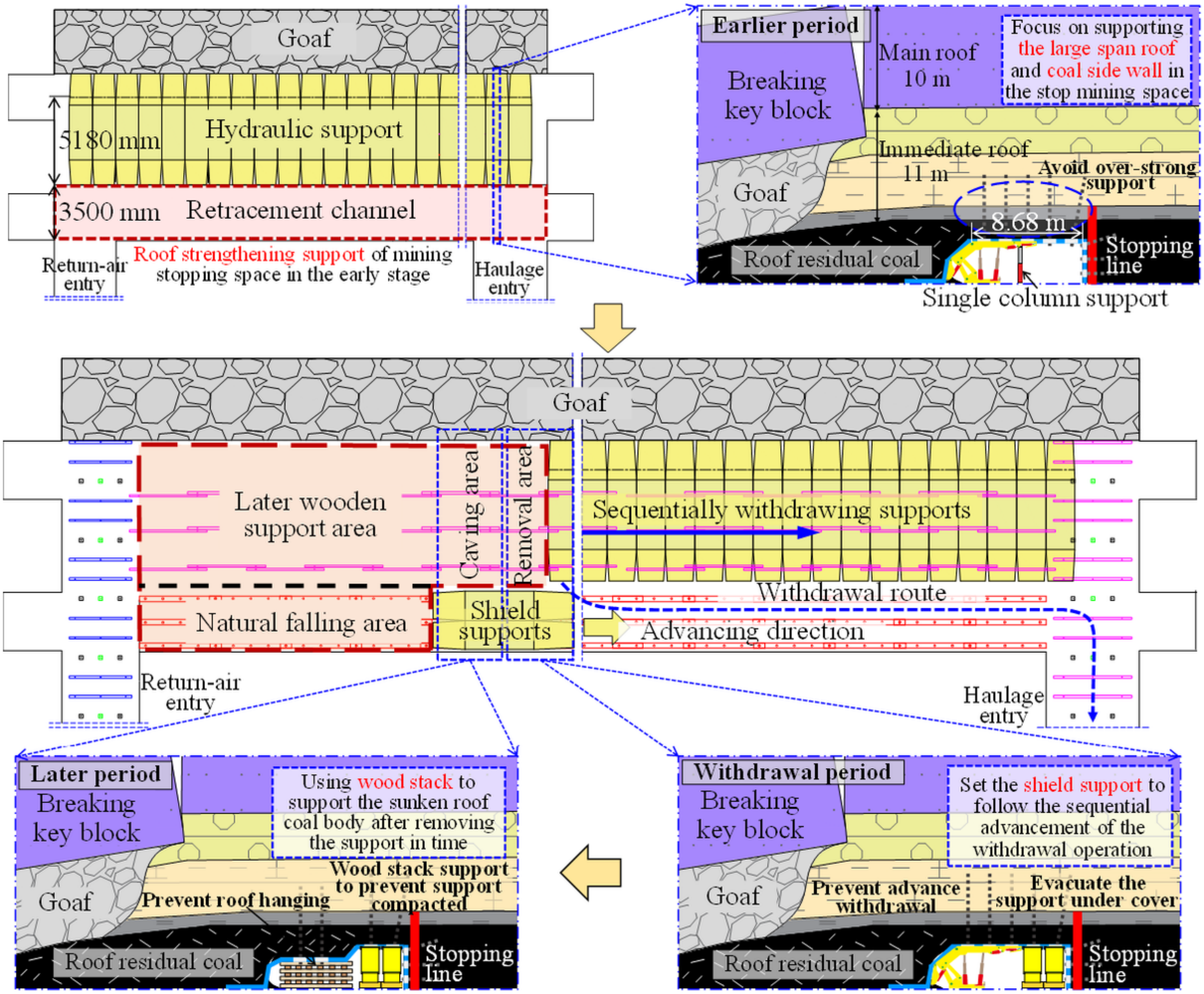


Figure 14

Support period divided by the support withdrawal process

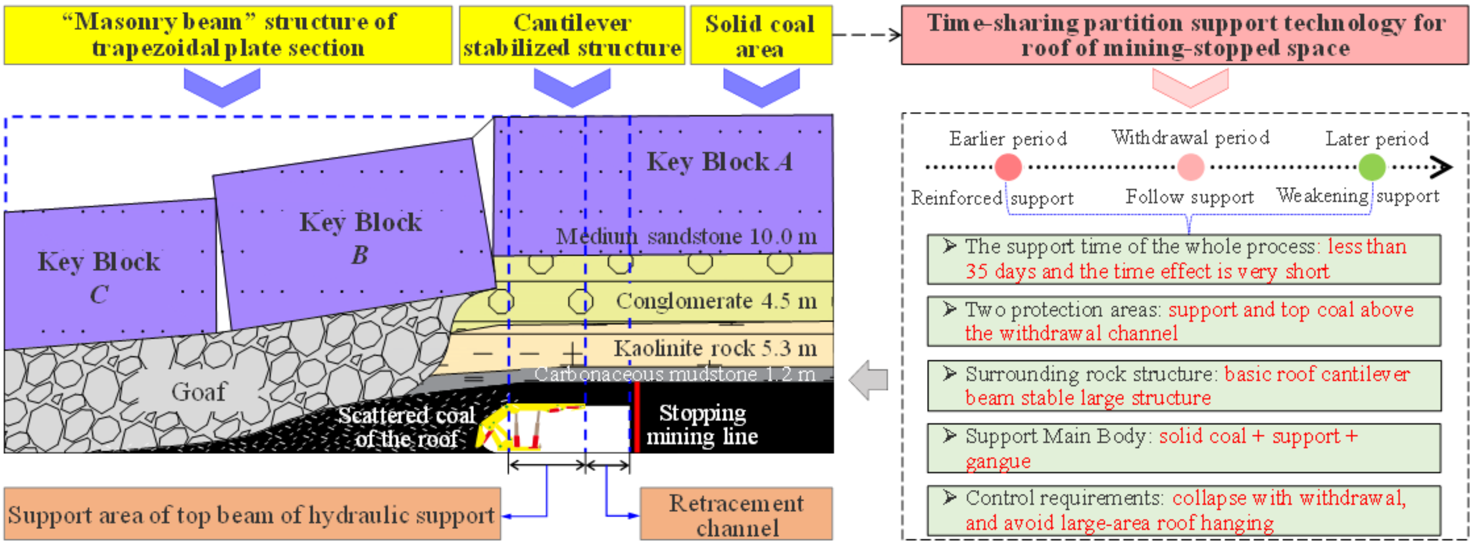


Figure 15

The idea of time-sharing partition support for the roof of mining-stopped space

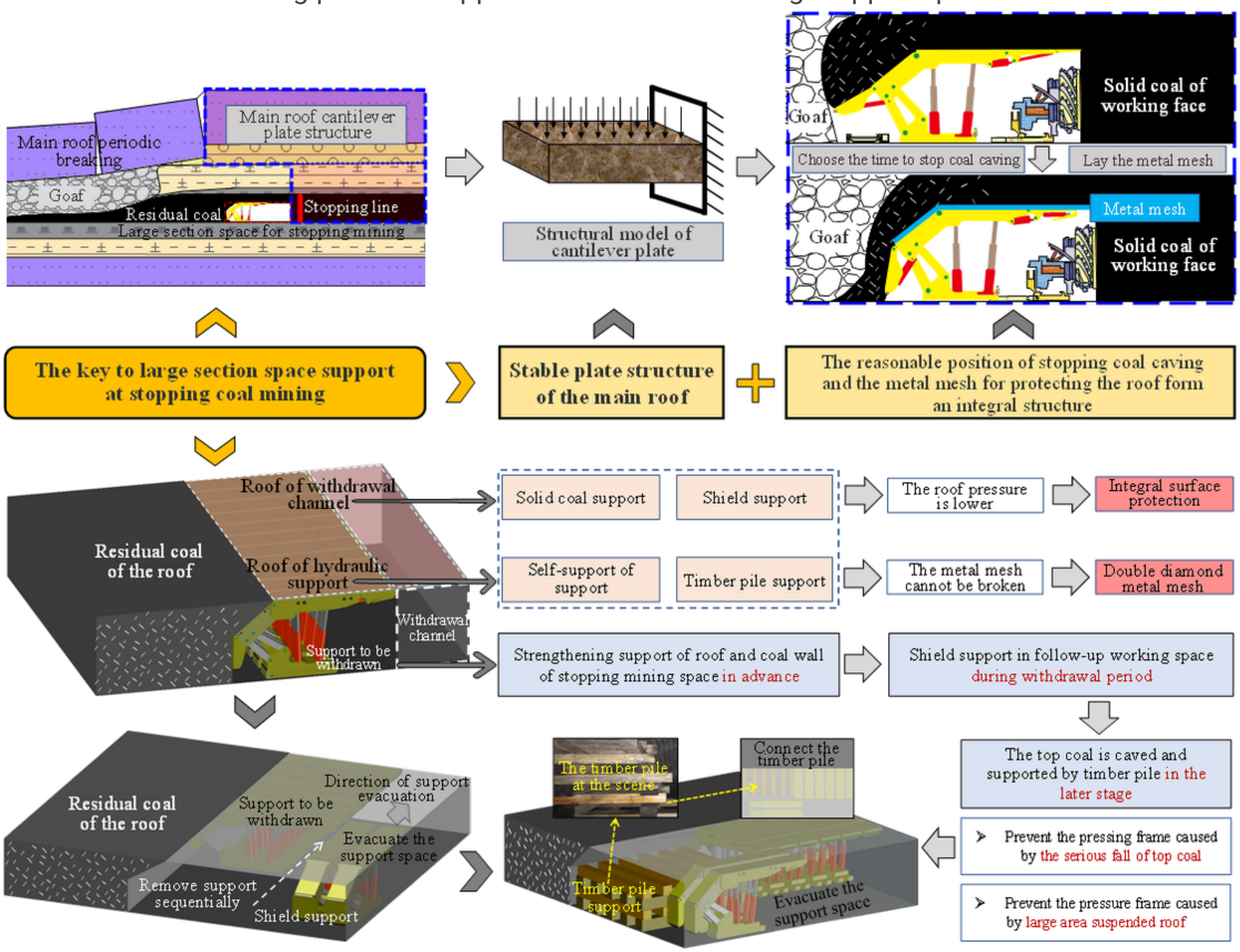


Figure 16

Key steps of large section space support at the stopping place

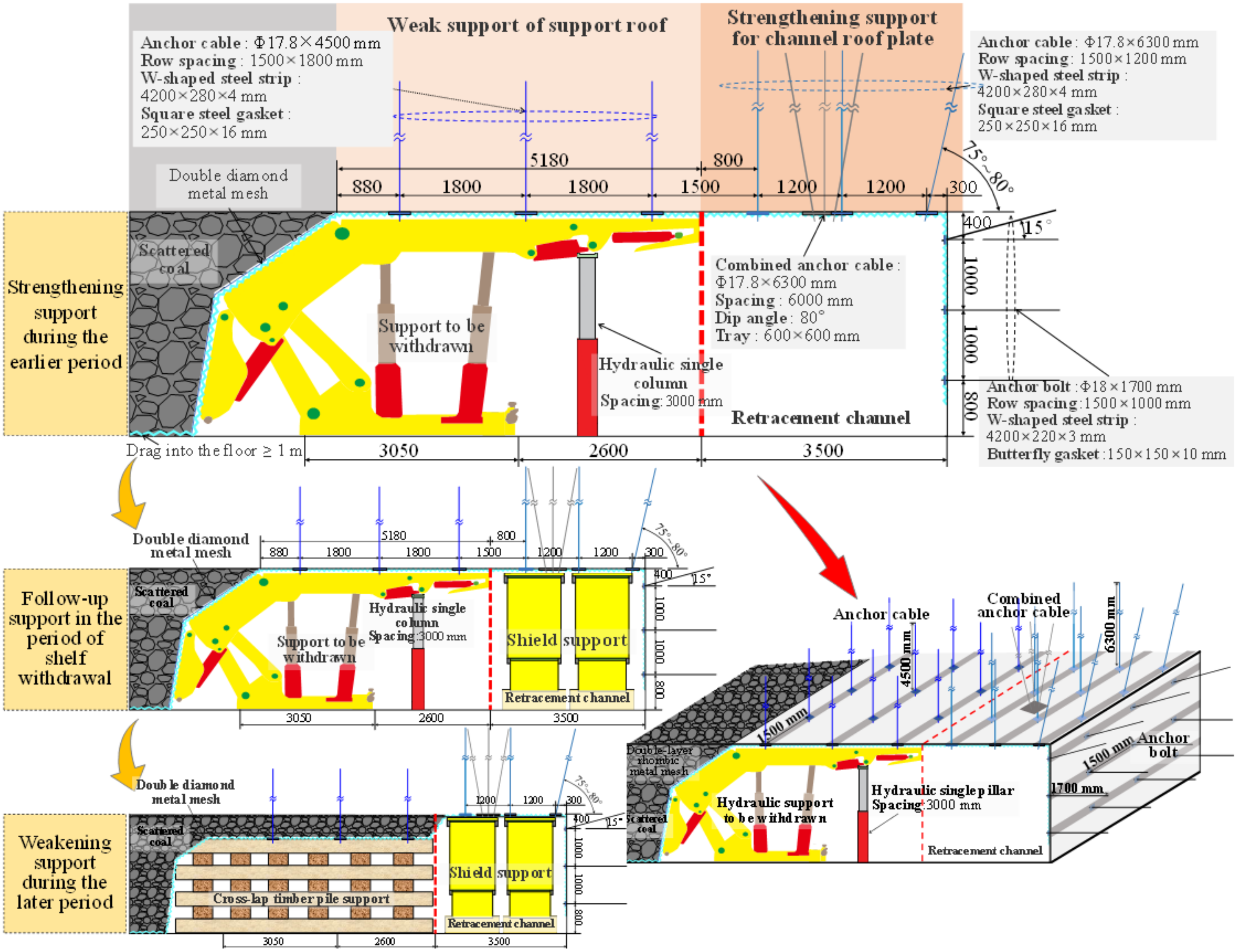


Figure 17

Scheme diagram of time-sharing partition support

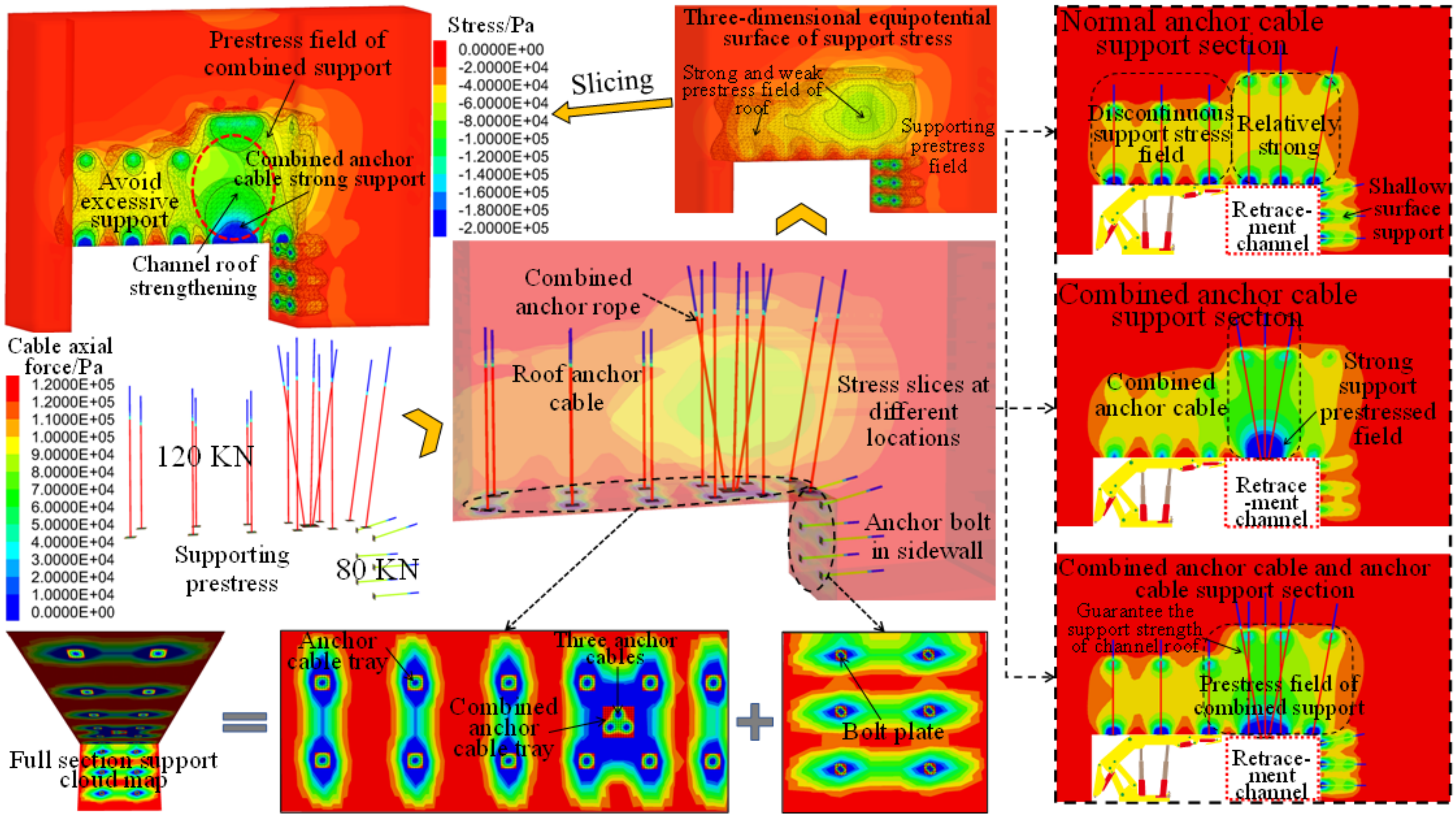


Figure 18

Cloud picture of the prestressed field of large section space support

Figure 19

Effect diagram of field application