Int j simul model 23 (2024) 2, 263-274
Original scientific paper

PRESSURE EVOLUTION OF OVERLYING ROCK STRATA USING GRADUAL INCREASE SUPPORT MINING METHOD

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Abstract
To improve the recovery for corner coal left over in mines, taking the Xin'an Mine in China as the research object, the gradual increase support mining method for recovering corner coal is proposed in this study and the evolution of the overlying strata pressure is investigated. The dynamic process of the overburden roof in the corner coal and the hydraulic support were simulated by using FLAC^{3D} software. Results show that, under the gradual increase support mining, the abutment pressure over the mining working face is less than 21 MPa. The overlying rock over the coal seam roof forms a periodic breaking–collapse cycle with a periodic pressure step distance of 10 m and the hydraulic support load is 13–25 MPa. Based on that, the gradual increase support mining method including a scheme of three supports and three chutes adding for every 9 m is designed and the corner coal is fully recovered. The obtained conclusions provide a significant reference for predicting strata movement over the corner coal, which can help aid in designing such mining method in engineering applications.
(Received in February 2024, accepted in April 2024. This paper was with the authors 1 month for 2 revisions.)

Key Words: Corner Coal Mining, Increasing Hydraulic Support, Numerical Simulation, Overburden Strata Movement, Field Application

1. INTRODUCTION

With the application of mechanized comprehensive mining technology, the production of coal has been increased significantly. Given this scenario, the contradiction between the finiteness of coal resources and unlimited consumption demand has become increasingly prominent. Hence, the recovery of coal resources must be improved [1, 2]. The effective treatment of corner coal in coal mine has several advantages beyond the enhanced efficiency of coal mining. For instance, it reduces the space where water and gas accumulate in the underground gob. Furthermore, proper treatment reduces the possibility of accidents, such as water inrush, gas explosion, harmful gas outburst, and the spontaneous combustion of residual coal in the gob. Such solution can also inhibit the dynamic movement of the coal seam as well as the roof and floor. Overall, it can improve the degree of mine safety [3, 4]. However, changes in the conditions of the coal seam cause difficulty in mining corner coal, thus resulting in a waste of resources. Given this urgent problem, technologies that can offer solutions to realize the mechanized mining of corner coal must be developed.

In view of the exploitation of coal resources with a regular shape, continuous mining and fully mechanized mining methods have mostly been used [5]. However, given the formation of faults, mining planning, etc., the corner coal may be recovered by using redirection longwall mining. This method does not completely solve the problem because it just changes the layout of the working panel, and irregular corner coal could appear when designing the layout of the next working panel. In addition, the room-and-pillar mining method could be applied for the mining and recovery of corner coal. However, the recovery ratio of this method is very low. In summary, both these methods have several drawbacks, such as the wastage of coal resources, the high cost of production equipment, and the low recovery of corner coal [6]. To achieve a production mode with less cost, safety and convenience for coal production, taking the Xin'an

Mine in China as the research object, the movement of overburden strata in the corner coal by numerical simulation and field measurement is analysed. The stress and failure of the surrounding rock during the mining process are predicted which can reveal the evolution of the overlying strata pressure. The findings of this study can help popularize the use of gradual increase support mining method in mining the corner coal and improve the mine's recovery ratio in the future.

2. STATE OF THE ART

Most studies have been conducted on the topic of corner coal mining. Although various methods and processes can be applied to corner coal mining, they are mainly selected and determined according to the occurrence status and geological conditions of the corner coal. To ensure the safe and efficient mining of corner coal blocks, a mechanized mining method that uses a continuous miner under extremely irregular coal body is proposed based on the key mining technology of corner coal under different geological conditions [7]. The optimization solves the problems existing in the field application of process technologies, such as main conveying system, cable retraction, mining ventilation, and walking support [8-10]. Zhao et al. [11] proposed a design scheme for the continuous mining of an inverted L-shaped working face for irregular corner coal mining, which ensured the continuous advancement of the working face and expanded the adaptation range of fully mechanized mining. In addition, Zhang et al. [12] designed the remining process of progressive increase of corner coal and conducted a numerical simulation according to the geological conditions of the working face. They examined the change law of surrounding rock stress in corner coal mining. Then, they optimized the surrounding rock support scheme in the mining process and improved the mining efficiency in the block section of the corner coal. Kumar et al. [13] found that the acute angle of parallelepiped corner coal is stressed and prone to failure. These failures may be attributed to a deterministic safety factor that does not consider the uncertainty of the geotechnical engineering in the field in the design parameters. Therefore, substantial research has been conducted on corner coal mining under soft coal and rock conditions. To examine the influence of roadway location on corner coal mining and the optimal location of roadways, a method was proposed to determine the ideal position of roadways in the middle residual coal seam based on 20 factors, which include stress, stress change rate, and fracture characteristics [14]. Wang and Xie [15] used FLAC^{3D} software to discuss the design of a safe pillar width for longwall mining under soft geological conditions. Furthermore, regarding the appearance law of mine pressure during the mining process, scholars have conducted research on the influence of different propulsion directions on the horizontal and vertical maximum stress [16]. Through similar physical experiments, Vinay et al. [17] simulated the stress evolution process in the fracture zone around the rectangular roadway under the influence of mining. Furthermore, Zhang et al. [18] established a numerical model of shallow buried deep coal seams in large mining heights using FLAC^{3D}. Then, they divided the roadway into plastic stress field, elastoplastic stress field, and elastic stress field according to the magnitude of roadside stress. By monitoring the support pressure, a new method for calculating the stress concentration coefficient was proposed. Most of the current research on corner coal mining technology comes from the direct formulation of plans through on-site observations in mines [19] and most of the mine strata pressure patterns are based on the mining working faces with a regular coal body. The control and management of overlying rock strata, stability maintenance, and the overall deformation of surrounding rocks in mining such irregular coal bodies remain insufficient [20-22]. Hence, exploring the effects of unique mining method and parameters on the overlying strata pressure on roofs and mine roadways is of great significance for the safe and efficient mining. Taking the Xin'an Mine in China as the research object, this study uses numerical simulations to reveal the pressure and movement deformation of the overlying rock strata when applying the gradual increase support mining method and the simulation results are verified in the field testing. Both of them provide a theoretical basis for guiding the applications of corner coal mining in underground.

The rest of this study is organized as follows. Section 3 describes the study scope, method and input data. In section 4, the horizontal and vertical stress changes of the upper overburden rock and the evolution of the surrounding rock during the advancement of the working face are analysed. Then, the simulation results are applied in the field. Section 5 summarizes the study and gives relevant conclusions.

3. METHODOLOGY

3.1 Study area

The Hebei province is one of the provinces with the largest mining scale in China. The Xin'an mine with a mining history over 30 years has a lot of irregular coal resources left, which are ready for mined out in the future. Taking the 11210-1 working face as the study area as shown in Fig. 1 [23], the open-off cut is adjacent to the protective coal pillar and the 11210-3 working mining area is mainly adjacent to the west. The working face has several uphill and downhill roadways and is located in the 2# coal seam. The average inclination length of working face is 85 m, and the strike length is 950 m.

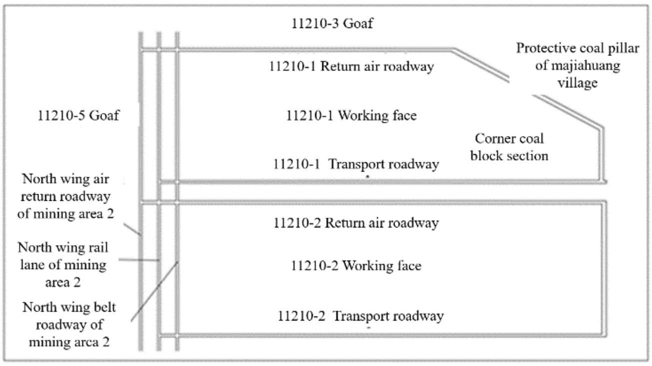


Figure 1: Layout of working face 11210-1.

The study area is in the shape of a square trapezoidal section. The layout and advancement of the mining process in the working face are shown in Fig. 2. The length of the working face varies greatly, and the size is irregular [24]. As the working face moves forward, the length of the open-off cut increases gradually from 50 m to 125 m. One support needs to be docked and advanced by 3 m, thus requiring a total of 48 supports and 48 scraper conveyors in the middle slot. According to the geological condition of the working face, three additional hydraulic supports and inclined troughs will be designed for every 9 m in advance.

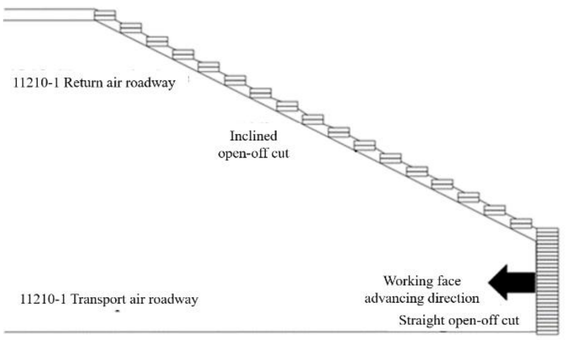


Figure 2: Diagram of working face layout and advancement.

The working face of study area is arranged with 33 stands in the straight open-off cut and 48 stands in the inclined open-off cut with an equal staggering of every three stands at a distance of 9 m. As the working face advances, additional bracing and slanting grooves are added. The empty roof part between the inclined open-off cut and the coal gang is supported by DW45-250/110X monolithic column with Φ300 column cap and column shoe, as well as two monolithic columns in each row and a column spacing of 2.3 m. The distance between the monolithic column and the adjacent coal gang is 0.5 m, and the row spacing is 1.3 m.

3.2 Numerical model setup

The numerical calculation model is established with the engineering geology of the 11210-1 working face of Xin'an Mine, as shown in Fig. 3. The corner coal of 11210-1 working face is adjacent to the 11210-2 mine gob in east and the three main downhills in south. The numerical calculation model takes the working face strike direction as the X axis, and the length of the open-off cut of the 11210-1 working face of is gradually extended from 50 m to 125 m. The Y axis follows the working face inclination direction and 170 m is taken along the direction. The vertical direction is the Z axis. The top roof of the working face is taken 37 m upwards, and the floor is taken 5 m downwards. Hence, the size of the whole model is 160 m × 170 m × 42 m.

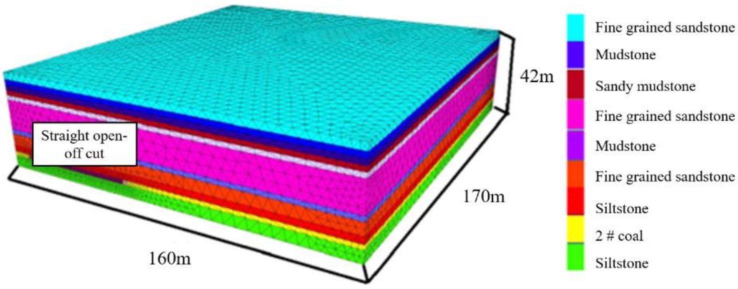


Figure 3: 3D of the numerical model.

The hydraulic support was created by 3D modelling software and was imported into FLAC^{3D} software to simulate the dynamic process of increasing the hydraulic support during the excavation of the working face. The dimensions of the hydraulic support are 3 m × 1.5 m × 2 m. The mine gob is filled with elastic materials to simulate the fall of gangue [25]. At the same time, a protective coal pillar is left at the working face boundary to simulate the original rock stress zone and reduces the boundary effect. To simplify the calculations, three hydraulic supports are initially placed at the right end of the working face, and the model cycle excavation step is 9 m. Three additional hydraulic supports are added to simulate the excavation process of corner coal, as shown in Fig. 4.

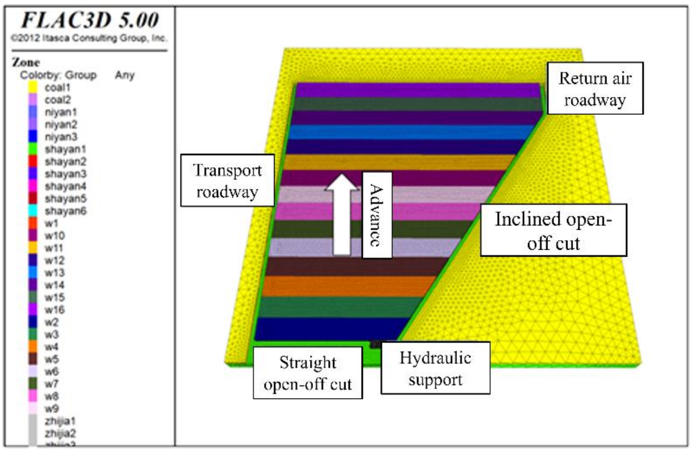


Figure 4: Excavation process.

The rock mass has prominent mechanical properties because of the geomechanical action of the joints and cracks. Most of the rock mass is yielded or damaged by the shear stress and has little or no tensile energy [26]. Therefore, the Mohr-Coulomb model is adopted to examine the rock formation, and the model parameters are given, as shown in Table I.

Table I: Table of physical and mechanical parameters of rock formations and supports.

Surrounding rock	**Thickness** (m)	**Density** (KN·m^3)	**Bulk modulus** (GPa)	**Shear modulus** (GPa)	**Internal friction angle** (°)	**Cohesion** (MPa)	**Tensile strength** (MPa)
Fine-grained sandstone	3.0	2873	10.22	6.83	42	2.8	1.3
Mudstone	2.4	2461	3.1	1.8	30	1.1	0.8
2# Coal loading	2.4	1380	4.91	2.01	32	1.2	0.45
Fine-grained sandstone	2.1	2873	8.25	5.10	34	1.1	1.3
Sandy mudstone	2.1	2510	3.45	1.89	31	1.2	0.24
Fine-grained sandstone	12.9	2873	12.10	8.82	42	3.2	1.29
Mudstone	2.1	2461	3.1	2.1	32	3.1	0.35
Fine-grained sandstone	5.0	2873	6.83	4.4	35	2.8	1.3
Siltstone	3.0	2630	5.0	3.8	35	3.2	2.1
2# Coal	2.0	1380	3.1	1.8	30	1.1	0.6
Siltstone	4.9	2630	5.5	4.0	35	3.1	1.8
Hydraulic supports	-	7850	115	85	-	-	-

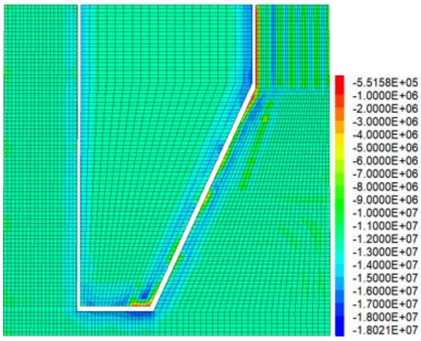
3.3 Field testing

Based on the numerical simulation results and on-site production practices, the 11210-1 working face was analysed on site and the mining plan was improved. The electronically controlled liquid tank of each group of hydraulic supports on the working face can display the pressure, monitor the working resistance of the support pillar in real time, and explore the pressure change of the working face through the working resistance of the support.

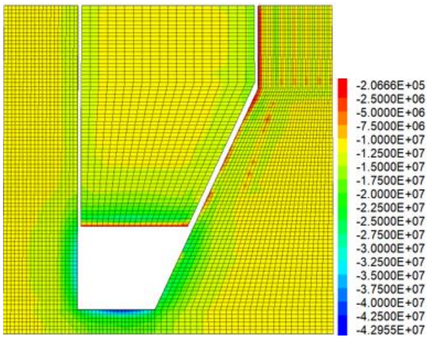
4. RESULT ANALYSIS AND DISCUSSION

4.1 Vertical stress changes during the advancement of the working face

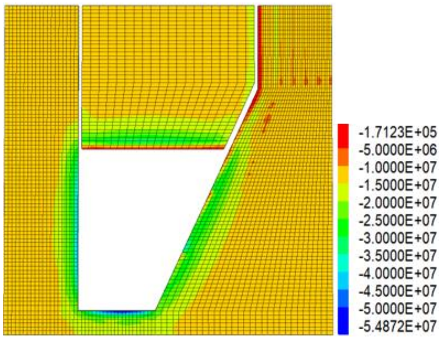
Fig. 5 shows the distribution of the stress field in the vertical direction of the coal at different advancing distances. The advancement direction of the working face is used as the profile. The stress concentration area is mainly concentrated in the surrounding rocks within 20 m of the roadway gang, and the stress concentration in the surrounding rocks of the open-off cut is more serious because the cross section of the open-off cut is larger than the cross section of the groove [27]. The peak vertical stress is mainly concentrated in the range of 10–15 m of the roadway gang, and a more severe stress concentration can be observed at the two ends of the working face. Notably, the peak vertical stress can reach 18.9 MPa. As the working face advances, the initial incoming pressure occurs at 15 m; the vertical stress of the working face coal gang increases to 21.63 MPa, and the supporting pressure reaches the peak at about 5 m in front of the coal wall [28]. At 30 m, the working face is under periodic pressure. Moreover, the vertical stress of the coal gang at the working face is 20 MPa, and the stress concentration factor is 2.0. The step of the old top periodic pressure is 10 m, and the peak support pressure is located about 4–5 m in front of the coal wall with a value of 18.4–20.6 MPa. Compared with traditional longwall mining faces, the length of the corner coal working face gradually increases, and the phenomenon of roof collapse and weighting is not as severe as that of longwall mining faces. In addition, precracking of the mining roof was conducted in the 11210-1 working face. During the mining process of the working face, the support pressure of the coal wall and roof weighting are not obvious, thus greatly increasing the safety of mining the working face.



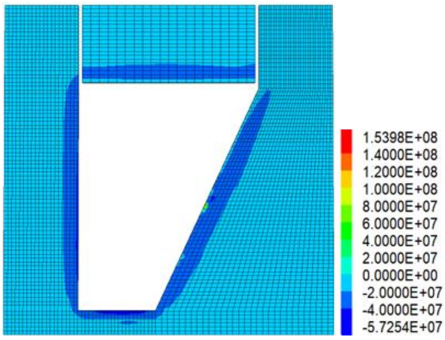
a) Working face not excavated



b) 50 m excavation of working face

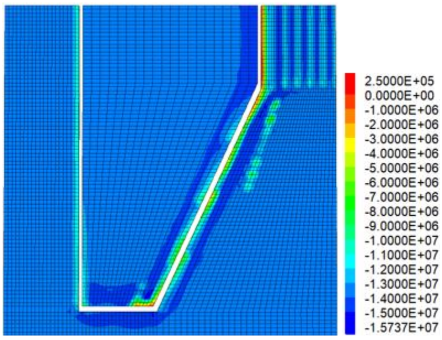


c) 100 m excavation of working face

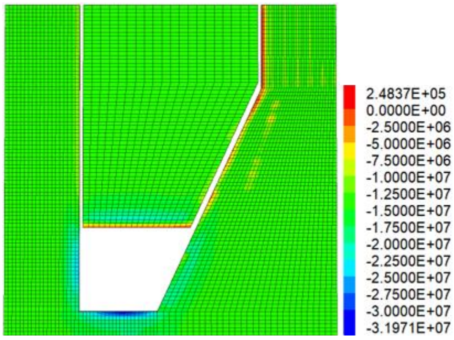


d) 150 m excavation of working face

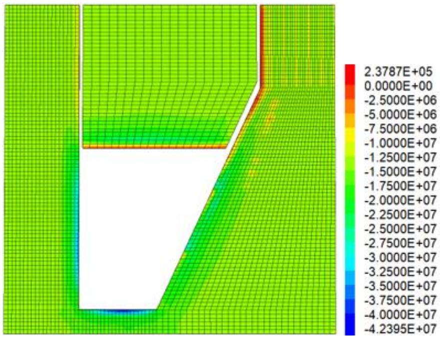
Figure 5: Distribution of stress field in the vertical direction of the coal in the working face at different advancing distances.



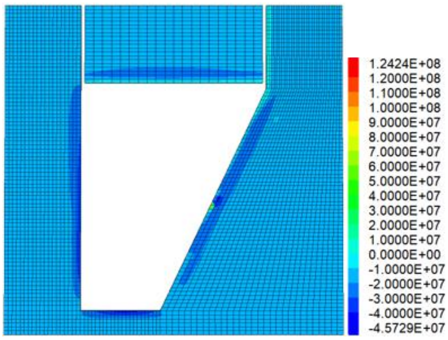
a) Working face not excavated



b) 60 m excavation of working face



c) 120 m excavation of working face



d) 175 m excavation of working face

Figure 6: Distribution of stress field in the horizontal direction of the coal in the working face at different advancing distances.

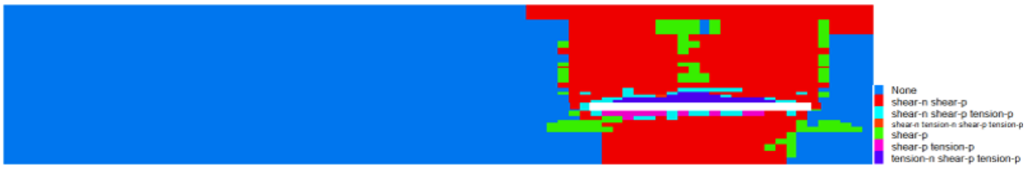
4.2 Horizontal stress changes during the advancement of the working face

Fig. 6 shows the distribution of stress field in the horizontal direction of the coal in the working face at different advancing distances. After the balance of the excavation along the open-off cut and the groove, a certain degree of stress concentration is generated in the open-off cut and the groove. The stress concentration area is mainly in the surrounding rock within the range of 20 m of the roadway, and the stress concentration of the surrounding rock in the open-off cut area is more serious because the open-off cut section is larger than the groove section [29]. The peak horizontal stress is mainly concentrated in the range of 10–20 m of the roadway gang, and the stress concentration is more serious at the two ends of the working face. Moreover, the peak horizontal stress can reach 15.73 MPa. During the forward retrieval process of the working face, the peak horizontal stress is located in the range of 5–10 m in front of the coal wall, and its value is 16.4–19.6 MPa. During the retrieval of the working face, the horizontal stress of the coal wall and the incoming pressure of the roof plate are not obvious.

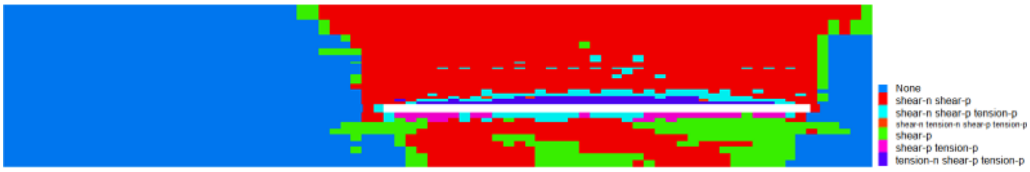
4.3 Analysis of the depth of damage and development pattern of the quarry roof

Fig. 7 shows the evolution of the plastic zone of the quarry roof at different advancing distances on the 11210-1 working face. The main consideration is that the rock with yield damage has already formed a mining disturbance fissure and the rock has already undergone plastic damage.

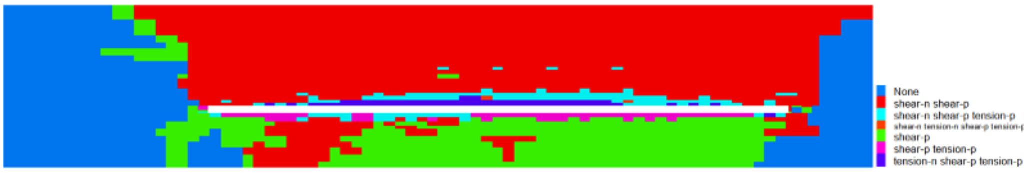
When the working face is advanced, the surrounding rock at the top of the working face is disturbed by mining. The stress is redistributed, thus resulting in the formation of caving zones, fissure zones, and bending subsidence zones in the overlying strata. The roof damage above the working face gob is mainly tensile damage, and the roof near the coal wall is mainly shear damage. The overall form of damage resembles a saddle-like shape. As the working face continues to advance, the tensile shear damage in the overlying strata of the working face continues to move forward and develop toward the upper strata.



a) 50 m advance on the working face



b) 100 m advance on the working face



c) 150 m advance on the working face

Figure 7: Evolution of the plastic zone on the quarry roof at different advancing distances.

4.4 Stress monitoring of supports during the advancement of the working face

To monitor the ore pressure law during the gradual increase support, five monitoring stations are selected at equal intervals between the end of the working face and the middle support. The measuring points are arranged in the front and rear columns of the hydraulic support, and the average value of the vertical stress was measured. The final result of the measured stress is shown in Fig. 8. When the initial excavation is 10 m, the vertical stress of the end support of the working face is 15 MPa. The vertical stress of the middle support is 13.23 MPa, which is less than the vertical stress on both sides. The large area of the overhang is not caused by it, and the roof is in a stable state. When the excavation is 20 m, the vertical stress of the end support of the working face is 18.9 MPa. Because the direct roof collapses resulting in local stress concentration [30-32], the vertical stress of the middle support is 21.32 MPa, which is higher than the vertical stress of the support on both sides. With the advancement of the working face, the vertical stress of the support in the middle of the working face is higher than the stress of the support at both ends. The maximum stress can reach 23.85 MPa. No significant difference is observed in the vertical stress of the supports at both ends of the working face, thus indicating that no evident mine pressure exists on the working face during the gradual increase support.

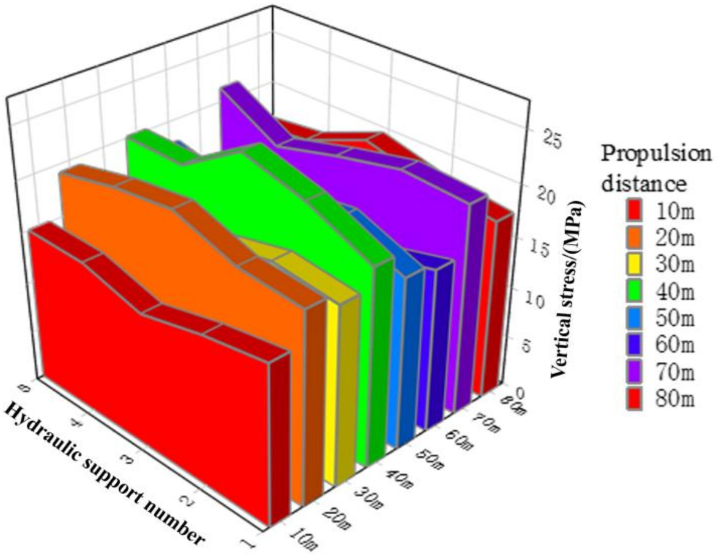


Figure 8: Monitoring stresses in different positions of the support struts.

The model excavation adds three hydraulic supports in the corner coal block section every 9 m to simulate the process of gradual increase support. The three hydraulic supports are monitored as the working face advances, as shown in Fig. 9.

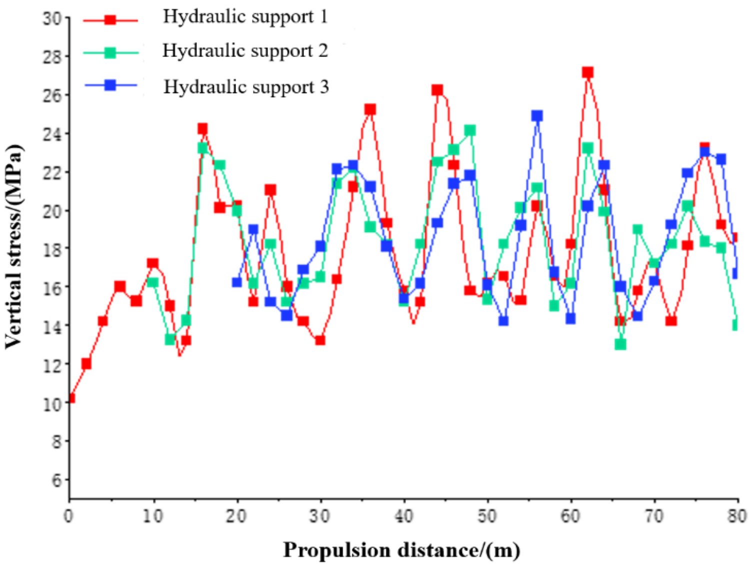


Figure 9: Support monitoring stress during the process of gradual increase support.

The results reveal the following: (1) The vertical stress of the support is 24.2 MPa at the initial pressure step of 15 m at the working face and 18.92 MPa on average at the periodic pressure step of 10 m. (2) The stress change of the three hydraulic supports is the same during the process of gradual increase support. Moreover, the pressure on the top plate is smaller, thus indicating that the top plate of the working face goes through the "stable – destabilized – stable again" process. (3) During the process of gradual increase support, the three hydraulic supports have the same stress change. The incoming pressure of the roof plate is small, thus indicating that the working face roof plate experiences the cycle of "stability – destabilization – restabilization". The sudden increase of the vertical stress of the support caused by structural instability also occurs in a cycle.

4.5 Application of gradual increase support mining

The 11210-1 working face of the corner coal block section is about 150 m long according to the field production practice. The working face advances by about 9 m with three additional hydraulic supports and three slanting troughs. One additional support and slanting trough need time to shift, the frame is increased 16 times in total. This process can prevent delays in the normal production of the working face. The time to increase the support and slanting is arranged in the maintenance team to increase and improve the support process gradually. This process has greatly improved the work efficiency of the face recovery and advancement.

The electric control fluid tank of each group of hydraulic supports in the 11210-1 working face can realize pressure manifestation and monitor the working resistance of the support pillars in real time. During the advancing process of the working face, the monitoring data of the working resistance of the progressive support is collected and collated. The relationship between the support pressure of the corner coal support and the advancing distance can be obtained by calculation and analysis, as shown in Fig. 10.

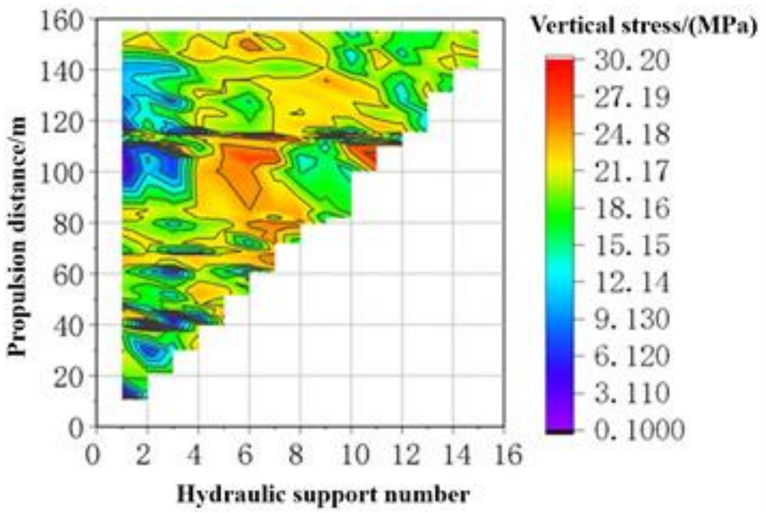


Figure 10: The support pressure of the corner coal support and the advancing distance.

The results show the following: (1) At the early stage of the corner coal mining, the support load is low, and the roof can maintain its own stability at this time. (2) When the corner coal advances to about 20 m, the support load increases to a maximum of 20.85 MPa because of the sudden increase in support load caused by direct roof collapse. (3) As the corner coal advances, the support shows low support load at both ends and high support load in the middle because of the roof. (4) With the advancement of the marginal coal, the overall support load is low at both ends and high at the middle support.

5. CONCLUSION

To solve the problem of coal resource recovery left over from corner coal, taking the corner coal of the 11210-1 working face of Xin'an Mine in Hebei Province, China as the research object, the gradual increase support mining method for corner coal was proposed in the study. Through the corresponding numerical simulation, the evolution of the strata pressure of the overlying rock and the dynamic working process of the hydraulic support were obtained. The calculation results were verified by field observations. Finally, main conclusions are shown as follows:

(1) Numerical simulation analysis shows that the peak vertical stress is mainly concentrated in the range of 10–15 m on the roadway, and the peak vertical stress at both ends of the working face can reach 18.9 MPa. With the advancement of the working face within the range of 15–30 m, the initial pressure occurs successively. It gradually increases to 21.63 MPa and then falls back to 20 MPa. The peak horizontal stress is mainly concentrated in the range of 10–20 m in the roadway, and the peak value can reach 15.73 MPa. In the aforementioned propulsion range, the value fluctuates within 16.4–19.6 MPa. The failure that occurs in the roof above the working face gob is mainly tensile failure, while that in the roof near the coal wall is mainly shear failure. The overall failure form resembles a saddle-like shape.

(2) The designed gradual increase support mining method includes 48 frames that need to be added at the roadway of the inclined open-off cut of the working face. Three supports and three chutes are added for every 9 m according to the working face conditions, and the frame is increased 16 times in total to improve the efficiency of mining and propulsion in the working face. The resistance pressure range of the support is 6.5–27 MPa, which is slightly higher than the simulation calculation results. However, the overall trend is consistent.

In summary, the gradual increase support mining method proposed in this study greatly address the problem of mining corner coal. In future research, the detection of advanced geological conditions in the mining area and the acquisition of the mechanical parameters of rock can aid in understanding the evolution of the overlying strata pressure.

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