

## Research Article

# Study on Stability of Stope Surrounding Rock under Repeated Mining in Close-Distance Coal Seams

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In order to study the influence of roof stress and fracture distribution characteristics on the stability of stope surrounding rock under repeated mining in close-distance coal seams, the research background of this paper is the close-distance coal seam mining of a mine in Guizhou province, China. The dynamic evolution characteristics of stope roof caving and the stress environment change law under repeated mining are studied by using the method of similar simulation experiment, numerical simulation, and field verification. The results show that the roof stage under repeated mining can be divided into four stages: normal mining, roof deterioration, end face roof leaks, and support crushing. The tip-to-face distance, support height, and support working condition are the main influencing factors in end face roof control. The main reason for the support crushing is that the roof above the support is broken, the main roof cannot form the self-stable structure, and the support force is insufficient. The roof dynamic load is high, and the subsidence of the end face roof is large, which is prone to roof caving during the stope roof weighting. Moreover, the roof weighting is frequent under repeated mining, which leads to the broken roof and the support cannot be supported, resulting in the occurrence of the support crushing accident. The control strategies for stope roof under repeated mining are provided based on the thorough study findings. The working face 17101 roof is successfully controlled by the aforesaid procedures, which provides the foundation for the management of stope surrounding rock under repeated loading.

## 1. Introduction

Close-distance coal seam refers to the coal seam with very close interlayer distance between two adjacent coal seams in the mining range of the mine field, and the mining can have a significant impact on each other. The mining areas with this geological condition are widely distributed in China. The end face roof leak of fully mechanized mining face is a common accident in coal mine production. The end face roof fall is the roof falling directly along the coal wall in the weak support area between the support and the coal wall. It not only directly affects the output and safety production of the working face but also increases the gangue content of coal, which is of great harm to production. The stope roof caving of fully mechanized mining face is a common accident in coal mine production, which not only directly affects the production and safety production of the working face but also increases the gangue content of coal,

which is harmful to production. Especially under the condition of close-distance coal seam mining, repeated mining makes the lower coal seam roof damaged, and the broken roof is easy to fall. During the mining process of the working face, the roof in front of the support collapsed, forming the end face roof leaks, which seriously affected the safe and efficient production of the working face. Therefore, it is an urgent technical problem to reveal the end face roof leak mechanism under repeated mining and ensure the stope roof controllability [1–4].

In terms of close-distance coal seam mining, domestic and foreign scholars have conducted a lot of research on the theory and close-distance coal seam mining technology, and many research results have been achieved. However, due to many influencing factors involved, the relationship between them is complex. The bearing structure characteristics of the overlying strata in the mined-out area in the close-distance coal seam mining are the main factors inducing

roof dynamic disasters. The bearing structure and stability characteristics of the overlying strata in the shallow-buried interval mined-out area of Yushenfu mining area in northern Shanxi were studied by numerical simulation, physical similarity simulation, and theoretical analysis [5]. In order to solve the instability problem of roadway surrounding rock under repeated mining in close-distance coal seams, the instability characteristics of roadway surrounding rock under repeated mining were studied by laboratory test, field test, physical similarity simulation experiment, and numerical simulation. The method of long bolt+high strength anchor cable+U-shaped steel+grouting is proposed to reduce the risk of surrounding rock instability under repeated mining and provide the basis for roadway support in close-distance coal seam mining [6]. In order to solve the environmental and safety problems caused by mining, it is one of the important links to control the development law and distribution characteristics of grazing rock fissures in mining. Through theoretical analysis to optimize the size of coal pillar in the lower part, use 3DEC numerical simulation experiment method to study the close-distance coal seam mining cracks. Scientific guidance is provided for reasonable division of coal pillar under repeated mining of adjacent working face in close-distance coal seams [7]. According to the deformation and energy release characteristics of surrounding rock under different mining sequences of close-distance coal seam group, the physical material similarity simulation experiment was carried out. Based on the comparative analysis of initial mining and upper mining of B4-1 coal seam, the characteristics of overburden strata movement, mine pressure distribution, and energy release in working face W1145 mining and residual coal mining are studied [8]. In order to explore the distribution law of stress field under the mining mode of gob-side entry retaining by roof cutting without pillar under goaf, based on the engineering background of working faces 8102 and 9101 in Xiashanmao mine, the stress field distribution of roof cutting without pillar and traditional remaining pillar was studied by means of theoretical analysis and numerical simulation [9].

In summary, scholars mostly studied the characteristics of roof caving, the law of surrounding rock movement, and the control of roadway surrounding rock in close-distance coal seam mining, and the stope roof stability was mostly single coal seam mining. However, the stope roof is damaged under repeated mining, which is more likely to cause disaster accidents of stope surrounding rock. Therefore, this paper studies the instability characteristics of stope roof in fully mechanized working face under repeated mining. Starting from the study of roof crack-stress under repeated mining, the crack propagation and stress evolution law of stope roof are obtained, so as to determine the dynamic evolution characteristics of stope roof instability and then put forward the corresponding control means, which provides the basis for the control of stope roof under repeated mining in close-distance coal seams.

## 2. Project Overview

*2.1. Mine Introduction.* The working face 17101 is the first mining face of the 17# coal seam in the mine. It mainly

mines the 17# coal seam. The mining depth is about 500 m, the average thickness of the coal seam is 3.6 m, and the average dip angle of the coal seam is 6°. The fluctuation is small, which is a near-horizontal coal seam. The direct roof of 17# coal seam is fine sandstone with a thickness of 3 m, and the basic roof is siltstone with a thickness of 5 m. The working face 17101 adopts comprehensive mechanized large mining height one-time mining full-height backward mining. The length of the working face is 150 m, and the advance length is 1000 m. Figure 1 is a comprehensive histogram of coal seam occurrence. The 15# and 16# coal seams are close to the 17# coal seam. The 15# and 16# coal seams have been mined out. Due to the influence of upper coal seam mining, the roof conditions of the 17# coal seam have changed, and the main roof and direct roof have been damaged to varying degrees. Roof accidents are prone to occur during mining.

*2.2. Overview of Roof Falling Accidents.* Since the 15# and 16# coal seams in the mine have been mined, 17# coal seam and 15# and 16# coal seams' spacing is small, and the 17# coal seam roof is damaged to a certain extent. During the mining process of working face 17101, the support moving method of timely support was adopted during the weighting period. However, there was still a serious end face roof leakage phenomenon in the working face. The roof caving height of No. 35 support reached 0.55 m, and the roof caving range reached 0.6 m × 1.2 m. Roof fall occurs mostly in the unsupported area from the beam end of the hydraulic support to the coal wall. The lumpiness of the leaking gangue is generally large, and the leaking gangue accumulates on the scraper machine, causing the working face to be forced to stop production and clean up. Obviously, the end face roof leakage phenomenon has brought serious influence to the normal mining of working face. It can be seen that because the working face 17101 is arranged under the goaf of 15# and 16# coal seams, the roof is affected by repeated mining, and the fully mechanized mining technology is used; the end face roof leak is more serious during the working face mining. Therefore, the instability characteristics of stope roof under repeated mining are studied, and the corresponding stope roof control method is proposed accordingly, which provides the basis for the stope roof instability control under repeated mining in close-distance coal seams.

## 3. Experimental Scheme Design

In order to explore the characteristics of end face roof instability under repeated mining, the roof weighting law, the end-face roof instability conditions, and the relationship among support-roof-coal wall under repeated mining were studied. In this paper, the similar simulation experiment is used to analyze the roof structure under repeated mining, and then, the influence of roof structure instability on the end face roof caving of 17# coal seam is analyzed, so as to obtain the end face roof leakage characteristics of 17# coal seam mining under the influence of repeated mining, which provides the basis for further analyzing the end face roof caving mechanism under repeated mining and puts forward the measures to control the stope roof stability from multiple perspectives [10–14].

Column	Rock name	Thickness/m	Lithologic character
	Fine sandstone	12.50	Hard, unbreakable, light gray, composed mainly of quartz.
	Siltstone	15.00	Hard, gray, horizontally stratified, slightly inclined stratified.
	Fine sandstone	7.00	Hard, unbreakable, light gray, composed mainly of quartz, containing plant carbonized debris.
	Silty mudstone	4.00	Soft, easy to destroy, dark gray, loose and fragile, good water absorption.
	Mudstone	4.30	Soft, easy to destroy, dark gray, loose and fragile, good water absorption.
	15# coal seam	1.20	Black, good coal, contains plant fossils.
	Sandy mudstone	2.00	Loose, easy to destroy, dark grey, horizontal bedding, loose and fragile, good water absorption
	Fine sandstone	4.00	Hard, unbreakable, light gray, composed mainly of quartz, containing plant carbonized debris.
	16# coal seam	1.50	Black, good coal, contains plant fossils.
	Siltstone	5.00	Hard, gray, horizontally stratified, slightly inclined stratified.
	Fine sandstone	3.00	Hard, unbreakable, light gray, composed mainly of quartz, containing plant carbonized debris.
	17# coal seam	3.60	Black, good coal, contains plant fossils.
	Mudstone	8.00	Loose, easy to destroy, dark grey, horizontal bedding, loose and fragile, good water absorption.
	Sandy mudstone	8.00	Loose, easy to destroy, dark grey, horizontal bedding, loose and fragile, good water absorption.
Medium sandstone	16.00	Hard, not easy to collapse, dark gray, block, patchy, strong water absorption, easy to weathering.	

FIGURE 1: Comprehensive histogram of coal seam occurrence.

3.1. Experimental Design and Parameter Determination

3.1.1. Experimental Model Design. The stope roof stability test is designed under repeated mining in close-distance coal seams, mainly considering the stability influence of stope surrounding rock in fully mechanized mining face under repeated mining. The physical similarity simulation experiment takes the geological conditions of fully mechanized working face 17101 as the engineering background, and the geometric size of the designed model is shown in Figure 2 [15–17].

As can be seen in Figure 2, a total of three coal seams were laid in the model. The model length was 300 cm, the model height was 150 cm, and 25 cm coal pillars were left at both ends of the model to eliminate the boundary effect. In the actual mining, 15# coal seam and 16# coal seam are first mined, and then, 17# coal seam is mined. The stope roof cracks and caving characteristics are studied in the process of 17# coal seam mining.

3.1.2. Determination of Similarity Ratio of Experimental Model

(1) Geometric similarity ratio

Model similarity ratio is the ratio of actual prototype length to model length:

$$C_t = \frac{L_p}{L_m}, \tag{1}$$

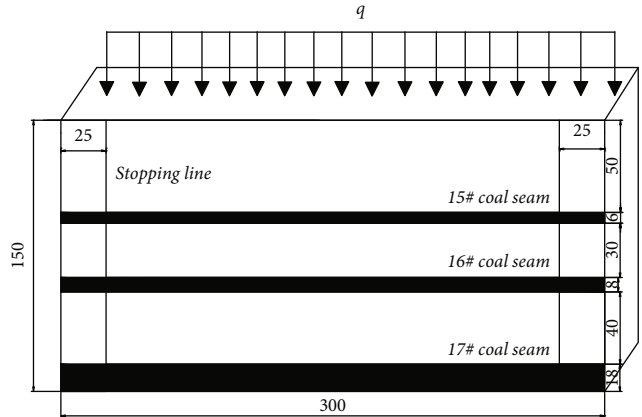


FIGURE 2: Model design.

where  $L_p$  is the length of the entity prototype and  $L_m$  is the model length.

In order to obtain the relationship among roof, support, and coal wall more intuitively and highlight the end face roof instability characteristics, the geometric similarity ratio of the simulation experiment is determined to be 20 : 1.

(2) Motion similarity ratio

In order to truly reflect the influence on the stope roof caving under repeated mining in 17# coal seam mining, the time effect should also be considered, that is, the motion

similarity coefficient of simulating the working face advancing process should be determined. In the experiment, the coal excavation process is required to maintain a certain proportion with the actual working face advancing process. Generally, it is determined by the similarity criterion of rock movement, that is, the motion similarity coefficient is the ratio of the prototype and the model time, which is equal to the second square root of the geometric similarity coefficient:

$$C_t = \frac{T_p}{T_m} = \sqrt{C_l} = 4.47, \quad (2)$$

where  $T_p$  is the entity prototype time and  $T_m$  is the model time.

### (3) Density similarity constant

In this physical similarity simulation experiment, the lithology of rock strata is mostly fine sandstone, siltstone, and mudstone in the engineering background prototype. Based on previous experimental experience and similar references, the bulk density similarity constant of this physical similarity simulation experiment is determined as  $C_\gamma = 1.7$ .

### (4) Stress similarity constant

According to the physical properties of coal and rock in engineering practice, the stress similarity coefficient of the model is  $C_\sigma = 32$ , combined with the actual situation of the experiment.

**3.1.3. Determination of Similar Material Ratio.** According to the actual engineering background, the similar materials selected by the similar simulation experiment mainly include sand, lime, gypsum, and mica. The sand and lime gypsum are mixed as the aggregate of coal and rock strata and mixed with water. According to Table 1, which is the physical and mechanical parameters of coal and rock, the mechanical parameters required by the model are obtained by combining the stress similarity ratio of the experimental model. The ratio of each coal and rock is obtained according to the parameter table. The quality of various raw materials required for this layer is calculated by combining the thickness and ratio of coal and rock. The demand for each material is summarized after calculating each layer, as shown in Table 2.

**3.2. Hydraulic Support Model Design.** In this experiment, the vertical hydraulic jack is used to simulate the hydraulic support column to provide the support force of the support model. The maximum support force of the jack is 20 kN, and the support height range is 150~310 mm, which meets the design requirements of the support model. After calculation, the support strength of the model support is 1.25 MPa, and the actual adjustable support height range of the support is 160~250 mm. The support model assembly product is shown in Figure 3.

As shown in Figure 3, the hydraulic support model is composed of hydraulic jack, pressure gauge, support base plate, connecting rod, support shield beam, support beams, and support telescopic roof beam. The hydraulic jack provides support force for the support, and the pressure gauge can monitor the roof pressure change. When using the jack, the oil valve should be tightened first, and the rocker should be inserted into the handle casing for pressure, so as to lift the support beam and provide support force for the support model.

## 4. Analysis of Experimental Results

**4.1. Initial Model Establishment.** This experiment is carried out on the two-dimensional similar simulation test bench of School of Mining, Guizhou University. The size of the experimental model is 3 m × 0.3 m × 1.5 m, and the actual simulation height is 30 m. Figure 4 shows the initial model. In this experiment, three layers of coal were laid, namely, 15#, 16#, and 17# coal seams. First, 15# and 16# coal seams are excavated; then, 17# coal seam is excavated. Since this experiment is mainly to observe the stope roof stability in the 17# coal seam mining process, therefore, this paper only analyzes the excavation of 17# coal seam.

**4.2. Mining Preparation Stage.** First of all, the 15# and 16# coal seams were excavated in order to simulate the actual effect. Figure 5 is the overlying strata collapse characteristics after excavation. From Figure 5, it can be seen that after the upper coal seam is opened, the 17# coal seam roof is damaged and fractured, and the self-stable structure formed by the overlying strata is easy to collapse again in the mining process of 17# coal seam, which affects the normal mining of 17# coal seam.

Figure 6 is the layout of the open-off cut in the working face of 17# coal seam. The open-off cut of the working face is simulated in the lower left corner of the model, and the support model is loaded for data collection by pressure gauge.

The experiment was started after the preparation work. When the model support was first lifted to support the roof, the initial support force was determined to be 2.2 kN by similarity theory calculation. The initial support force was determined by the reading of the pressure gauge in the experiment. In the experimental process, the determination of the initial support force needs to be determined by observing the broken state of the model roof and the mining height. Simulate shearer cutting depth 5 cm, reciprocating cycle, until the end of the experiment.

**4.3. Movement Characteristics of Stope Surrounding Rock under Repeated Mining.** In order to study the movement characteristics of stope surrounding rock under repeated mining in close-distance coal seams, the experiments were analyzed and studied from four aspects: normal mining stage, roof deterioration stage, end face roof leak stage, and support crushing stage, so as to obtain the movement characteristics of stope surrounding rock under repeated mining [18–22].

TABLE 1: Parameters for different rocks tested.

Category	Density, kg/m <sup>3</sup>	Cohesion, MPa	Bulk, GPa	Shear, GPa	Tension, MPa
Medium sandstone	2600	4.90	8.38	7.96	4.56
Siltstone	2540	3.20	6.85	5.47	3.86
Fine sandstone	2600	3.38	5.27	4.69	3.35
Mudstone	2450	1.24	4.16	2.83	3.02
Sandy mudstone	2500	1.34	4.36	2.53	3.52
Silty mudstone	2550	1.43	4.56	3.23	3.32
Coal	1350	0.50	3.95	2.20	1.04

TABLE 2: Model of similar material ratio of rock strata.

Lithology	Model thickness/(cm)	Layer number	Layer thickness/(cm)	Ratio	Sand (kg)	Lime (kg)	Gypsum (kg)
Fine sandstone sandstone	8.00	2	4	655	8.49	0.71	0.71
Silty mudstone	20.00	4	5	755	8.67	0.66	0.66
Mudstone	20.00	5	4	764	8.67	0.75	0.5
15# coal seam	6.00	1	6	855	8.81	0.55	0.55
Sandy mudstone	10.00	2	5	764	8.67	0.75	0.5
Fine sandstone	20.00	5	4	655	8.49	0.71	0.71
16# coal seam	8.00	1	8	855	8.81	0.55	0.55
Siltstone	25.00	5	5	664	8.49	0.85	0.56
Fine sandstone	15.00	5	3	655	8.49	0.71	0.71
17# coal seam	18.00	1	18	855	8.81	0.55	0.55

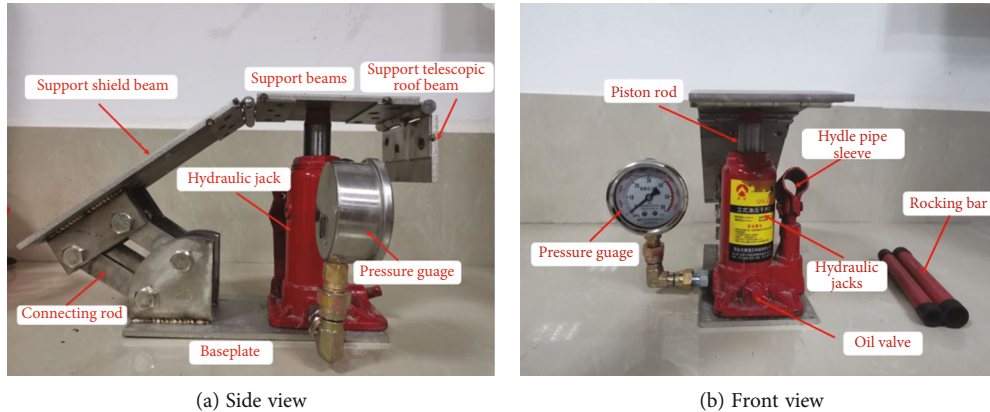


FIGURE 3: Model of hydraulic support.

4.3.1. *Normal Mining Stage.* The support installation was completed by the open-off cut of the working face. The model support cylinder loaded the lifting support roof for the first time. When the first cyclic mining is completed, the hydraulic support unloads and falls, and the roof above the support appears cracks. It can be seen that the supporting roof of the support squeezes and breaks the roof, and the support cyclic movement ends, as shown in Figure 7.

The direct roof at the rear of the support collapses in the process of moving the support with the continuous advancement of the working face. When the lifting support roof is loaded again, the support is normal, the end face roof is stable, and the surrounding rock of the stope is not abnormal, as shown in Figure 8.

4.3.2. *Roof Condition Deterioration Stage.* The mining cycle continues as the working face advances, and the support force squeezes the roof, causing a high number of fractures. The roof fractures are becoming more visible as mining progresses. The roof collapsing height behind the support grows as the support moves to hold the roof, and the fractures continue to expand higher. The roof above the support has developed transverse fissures, and the roof below the top beam is moving horizontally to the goaf. There is a layer of broken rock on the contact surface between the roof beam and the roof, which leads to the failure of comprehensive contact between the support and the roof and the poor support effect of the support, resulting in the “head down” of the support, as shown in Figure 9.

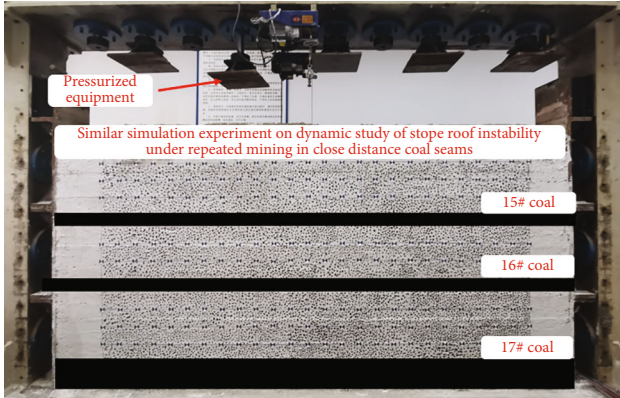


FIGURE 4: Initial model.

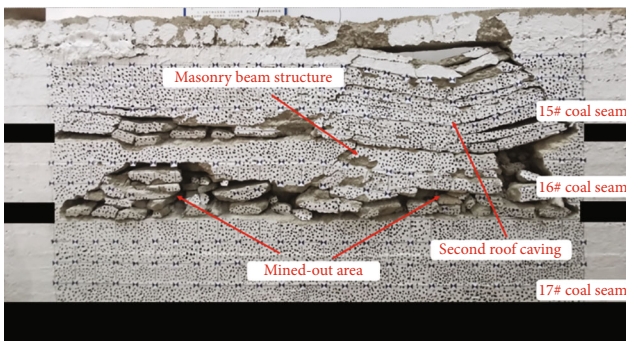


FIGURE 5: Characteristics of overlying strata collapse.

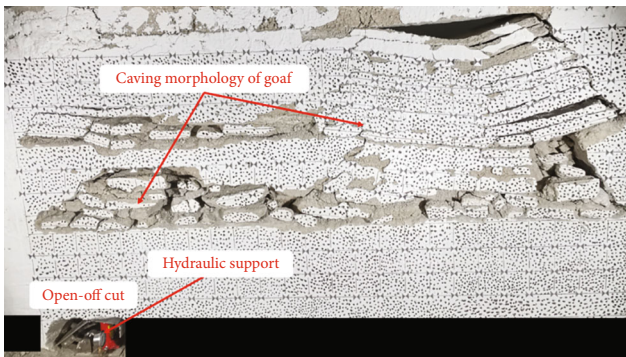


FIGURE 6: Open-off cut layout of working face.

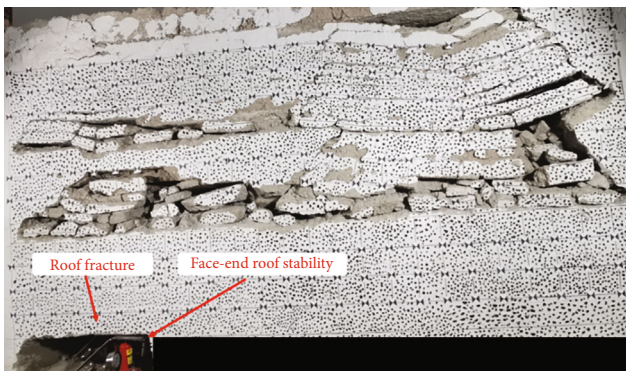


FIGURE 7: Roof state in normal mining.

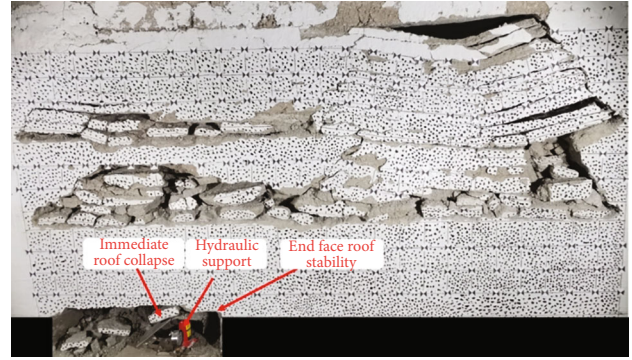


FIGURE 8: Roof state of immediate roof leaks.

In the process of mining, the roof cracks gradually increase with the quick rapid mining. The exposed area of the end face roof increases in the process of moving the support of the working face, and the roof cracks in the unsupported area increase. At this time, when the mining distance increases, the roof collapse may occur in the unsupported area in the process of moving the support, resulting in end face roof caving and affecting the working face mining. Therefore, it is necessary to support the end face roof in time to reduce the span and exposure time of the unsupported area, so as to control the stability of the end face roof, as shown in Figure 10.

With the continuous advancement of the working face, the self-stabilizing structure formed by the rock mass is used to forcibly move the support, so that the front beam of the support is close to the coal wall and the lifting support roof is loaded. In the support stage, the back part of the top beam is the broken roof. The roof cracks in the front part of the support top beam increase, and the central part is the compacted broken roof. At this time, the support needs to increase the support force to stabilize the roof, prevent the support “head down,” and cause the instability of the end face roof, as shown in Figure 11.

**4.3.3. End Face Roof Leaks Stage.** With the advancement of the working face, the roof condition is seriously deteriorated. The support is unloaded first, and then, the lifting is loaded. At this time, the end face roof leaks, and the end face roof failure and movement characteristics are caused by the increase of tip-to-face distance. The following analyzes the end face roof leaks from the precursor of the roof caving and the caving evolution process [23–25].

#### (1) Precursors of end face roof leaks

At the end of mining, the roof behind the top beam collapses to form a cantilever beam structure, which has a trend of rotation to the goaf. Due to the large tip-to-face distance, tension cracks are formed in the middle of the end face roof, and there is a risk of caving. Figure 12 shows the distribution characteristics of cracks before the end face roof leaks.

#### (2) Evolution process of end face roof leaks

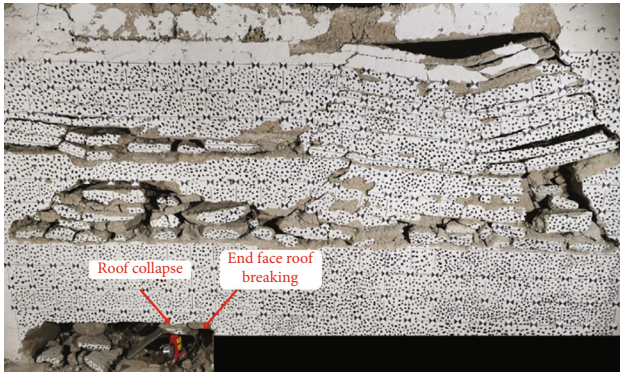


FIGURE 9: Deterioration of roof conditions.

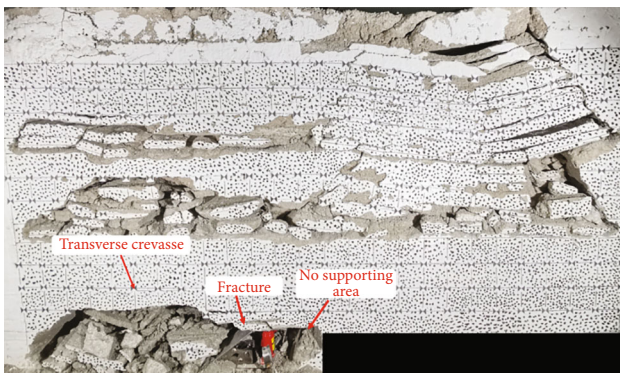


FIGURE 10: Exposed state of end face roof in moving process.

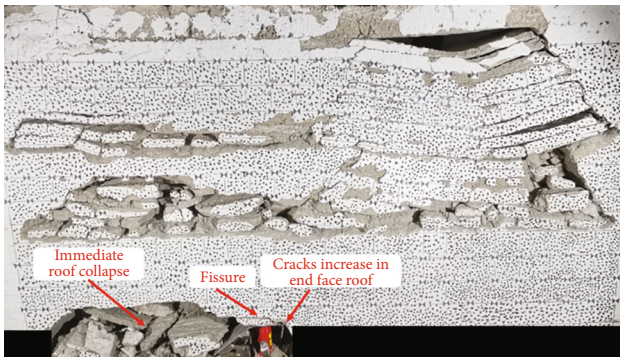


FIGURE 11: Further deterioration of roof conditions.

During the lifting process, with the increase of the support height, the roof above the top beam of the support produces upward displacement, and shear dislocation occurs with the roof of the front end of the frame, forming a near vertical crack through, and the roof of the end face is unstable and caving, and the space form is “arch.” At the same time, the cracks in the middle of the end face roof are developed, and there is a further caving trend. Subsequently, the support continues to load, and the end face roof falls again. The caving height is about 6 cm, as shown in Figure 13.

The morphological characteristics of end face roof leaks are as follows: the roof fall height expands again, and the roof fall space area increases with the increase of time. The

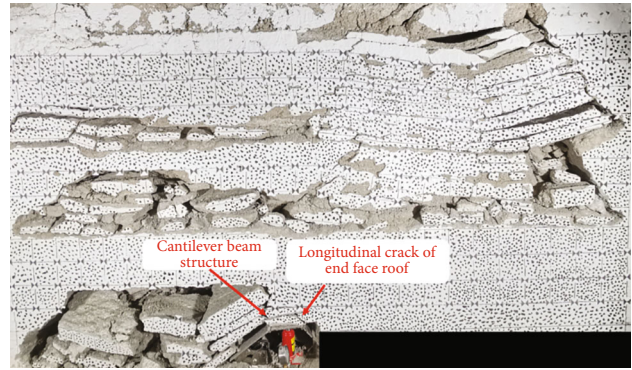


FIGURE 12: Distribution characteristics of cracks before end face roof leaks.

structure formed by the roof fall is a large bottom angle on one side of the support and a small bottom angle on the side of the coal wall, and the shape is approximately an “unsymmetrical arch.” As time continues to increase, the height of the roof does not change, and the space structure of roof caving is temporarily stable.

**4.3.4. Support Crushing Stage.** In the process of stope continuous advancement, the roof caving height increases continuously with the increase of mining span, and at this time, the main roof cracks increase, as shown in Figure 14. The working face continues to advance, and the main roof with cracks breaks. The gangue in the overlying goaf collapses with the main roof.

With the fracture of the main roof, the roof slab collapses to form a cantilever beam structure. During the mining process, the cantilever beam was unstable in its rotation, resulting in a support crushing accident, as shown in Figure 15. As shown in Figure 15(a), the roof behind the support collapsed, the transverse cracks increased, and cracks appeared at the end face roof in the process of working face advancing. As shown in Figure 15(b), a longitudinal large crack appeared in the roof with the continuation of advancing, resulting in an increase in the force at the back end of the support. As shown in Figure 15(c), the exposed of the non-support area increased in front of the support. In the process of moving the support, the roof behind the support collapsed in a large area, and the roof cracks in front of support further expanded, resulting in a relatively broken end face roof in front of the support, which was prone to end face roof leak accidents. As shown in Figure 15(d), the working face continues to advance, and the roof above the support makes a rotary sinking motion to the goaf. The support compression is reduced to 0, and the longitudinal cracks developed by the main roof and the direct roof cracks are interconnected. The roof above the support collapses, causing the support crushing, which leads to the roof at the front end of the support to collapse.

The movement characteristics of the end face roof of a fully automated working face were studied using a similar simulation experiment, and the interaction mechanism of “support-surrounding rock” and the development process of end face roof instability were investigated. Through the

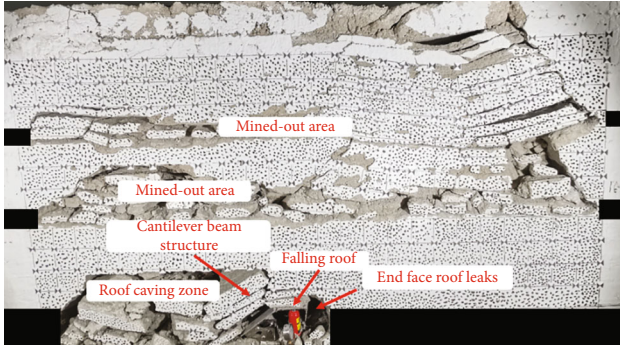


FIGURE 13: End face roof leak characteristics.

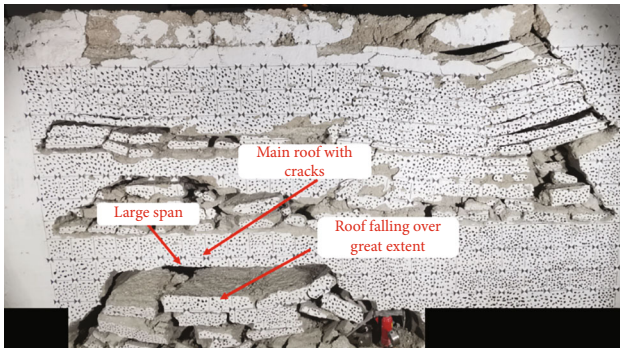


FIGURE 14: Fracture evolution process of main roof.

simulation of site surrounding rock conditions, hydraulic support roof control, and mining process, four types of site conditions, including normal advance, roof deterioration, end face roof leaks, and support crushing, were successfully reproduced in fully mechanized working face. The dynamic evolution characteristics of macro large damage and large displacement of stope surrounding rock were analyzed. The following is a summary:

- (1) In the stage of roof deterioration, it is found that the roof is damaged and destroyed under the repeated mining in close-distance coal seams. The damaged roof in the fully mechanized working face is squeezed under the combined action of the support force and the gravity of the overlying strata, resulting in the development of rock fracture and structural fragmentation. The roof span increases, and the roof behind the support falls with the continuous advancement of the working face. The roof above the support forms a free surface at the goaf side, and the height of the free surface increases with the increase of the advancing length and the roof fall height behind the support, which provides space for the roof activity above the support. In the two-dimensional plane, the stress state of the roof changes from two-way stress to one-way stress in the vertical direction, which promotes the increase of longitudinal tension cracks developed in the interior, and determines that the roof fall behind the support is a step-up process from bottom to top

- (2) In the end face roof leaks stage, it is found that with the advance of the working face, the support is unloaded first and then loaded with the lifting support, the roof condition is seriously deteriorated, and the destruction and movement characteristics of the end face roof are caused by the increase of the tip-to-face distance. At the end of the mining, the roof behind the top beam collapses to form a cantilever beam structure. When the cantilever beam structure is unstable, tension cracks are formed in the middle of the end face roof, and there is a hidden danger of end face roof leaks. During the rise of the support, the roof above the top beam of the support and the end face roof produce shear dislocation with the increase of the support height, forming vertical fracture coalescence, which is easy to cause the instability and end face roof. Therefore, the size of tip-to-face distance, support height, and support working state are the main influencing factors in end face roof control

- (3) It can be seen from the analysis of the support crushing in the experimental that the main reason for support crushing is that the roof above the support loses its self-stability. The penetration of the longitudinal cracks in front of the support is the direct reason for the failure of roof self-stability. The shear effect of the support excessive lifting on the end face roof can also induce the penetration of longitudinal cracks in front of the support. At the same time, the support height decrease leads to the separation of the upper rock layer. In the experiment, it is manifested as the dislocation of the main roof and the direct roof. The weakening of the interaction between the support and the main roof makes the direct roof turn to the goaf, further expanding the through cracks in front of the support, resulting in a large number of rocks falling into the working face. Therefore, the support role is to provide the support force required for the roof self-stabilization above the support to avoid the development of longitudinal cracks in front of the support

## 5. Numerical Simulation of Roof Caving under Repeated Mining of Close-Distance Coal Seams

In underground rock excavation, the UDEC numerical simulation software is used to analyze rock movement displacement and deformation under various lithologies and excavation circumstances. It can track and evaluate the stress state and distribution of a single point or side, as well as simulate stress and deformation characteristics of the supporting structure. Data, tables, and graphics are used to show the simulation findings. As a result, this research employs the UDEC numerical simulation software to examine the stress development of the stope roof at various advancing distances and puts forward corresponding control measures [26–29].



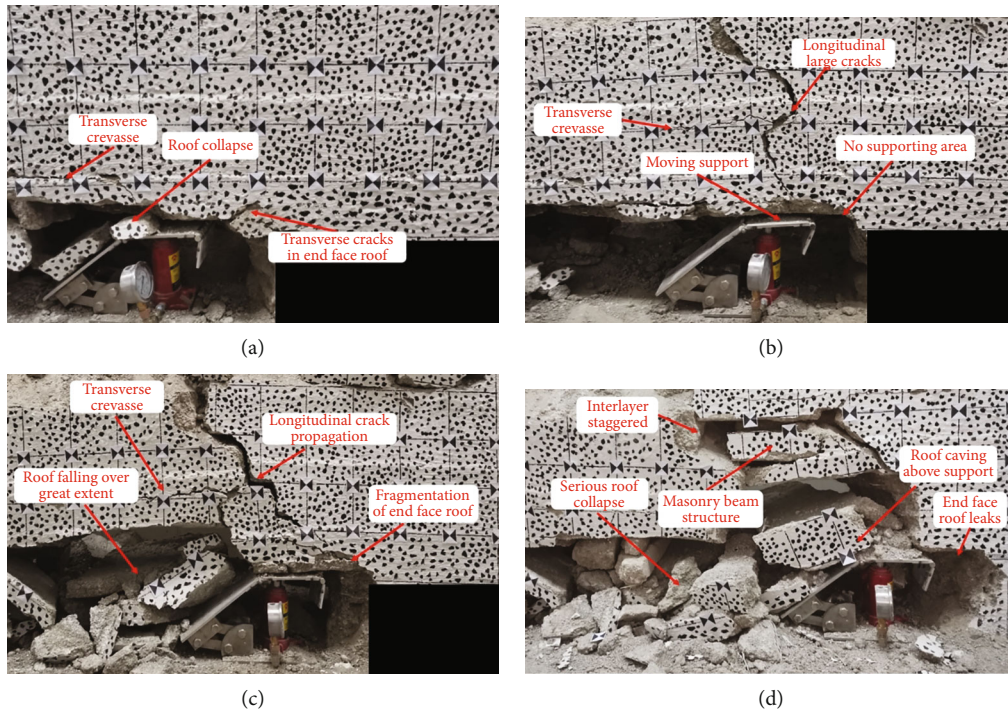


FIGURE 15: Evolution of support crushing under repeated mining.

5.1. *Establishment of Initial Model.* In order to analyze the stability of stope roof under repeated mining, the stability of stope roof is regarded as a two-dimensional problem, and a plane strain mechanical model is established. The length of the calculation model is 200 m, the height is 100 m, and the mining depth of the simulated working face is 500 m. In order to eliminate the influence of boundary, 40 m coal pillars are left on both sides, and a total of 120 m is excavated. The displacement constraint is used to fix the boundary at both ends of the model, and the upper unladen rock mass is applied to the model top in the form of uniform load. The numerical model is shown in Figure 16.

5.2. *Fracture-Stress Evolution under Repeated Mining.* Figure 17 is the fracture-stress evolution of 15# and 16# coal seams after mining. It can be seen from Figure 17(a) that after the mining of the 15# and 16# coal seams, cracks appear on the roof of the 17# coal seam, and the roof below the two ends of the goaf is the most obvious. The floor cracks of 16# coal seam have reached 17# coal seam. The stope roof is affected by multiple factors, and the stope roof is prone to collapse in the process of mining 17# coal seam. Therefore, measures should be taken in time to ensure the smooth mining of the working face. From the Figure 17(b), it can be seen that there is an obvious stress increase zone at both ends of the goaf and the stress decrease zone in the middle of the goaf, and the vertical stress decreases gradually in the area far from the ends of the mining space. In summary, the stope roof control is particularly important in the process of 17# coal seam mining, the crack distribution is dense in the two ends of the upper goaf, and it is in the stress increase

area. It is necessary to pay attention to the stability control of the stope roof in the mining process [30].

5.3. *Fracture Characteristics of End Face Roof in 17# Coal Seam Mining.* Figure 18 shows the stress distribution of 17# coal seam stope roof under different advancing distances. It can be seen from Figure 18 that when the working face advances 20 m, the direct roof falls without affecting the end face roof. At this time, the subsidence of the end face roof is small and relatively stable. When the working face advances 30 m, the main roof sinks to form a masonry beam structure, the end face roof deforms, the coal wall is affected, and the horizontal displacement changes. When the working face advances 40 m, the subsidence of the main roof becomes larger, and the dynamic load caused by roof weighting affects the end face roof subsidence, resulting in serious deformation of the coal wall. At this time, disasters such as end face roof leaks and rib spalling are prone to occur. When the working face advances 50 m, the large area of roof pressure causes the support crushing, and the stope roof caving is serious. At this time, the stope surrounding rock is extremely unstable. When the working face advances 60 m, the direct roof collapses and fills the goaf, the main roof fractures and sinks, the stope support is destroyed, the support capacity is lost, the stope roof collapses, and the coal wall deforms seriously. When the working face advances 70 m, the end face roof sinks and the coal wall deforms, but the coal wall and the roof are relatively stable at this time, indicating that it is not in the period of pressure.

Therefore, under the influence of 15# and 16# coal seam mining, the roof weighting of 17# coal seam is more

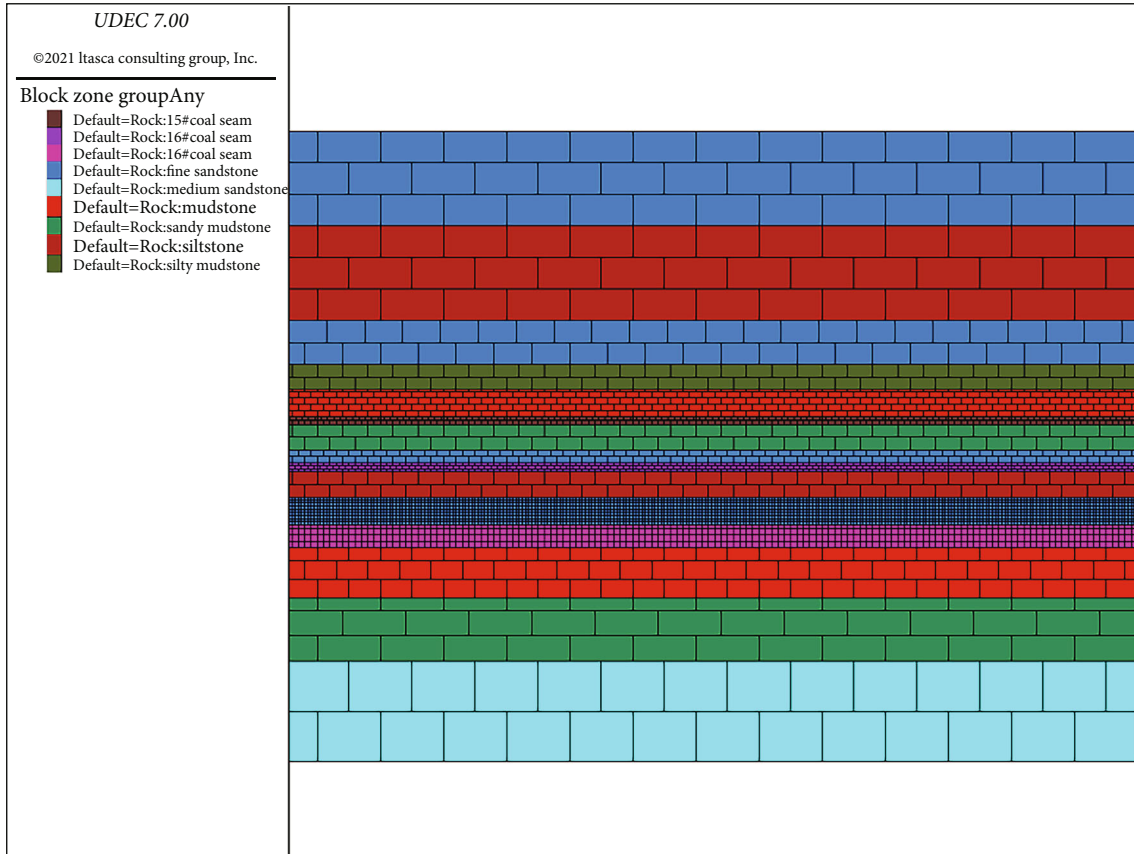


FIGURE 16: Numerical model.

frequent, and the stability of stope roof becomes worse. When the weighting causes large dynamic load, stope roof fall phenomenon is more serious. Therefore, it is necessary to pay attention to the roof weighting in time, so as to control the broken stope roof in time.

**5.4. End Face Roof Subsidence in 17# Coal Seam Mining.** Figure 19 shows the subsidence change of the end face roof under different calculation steps. It can be seen from Figure 19 that the end face roof subsidence increases with the increase of the advancing distance. When the advancing distance exceeds 40 m, the end face roof subsidence increases from -0.35 to -0.6. The larger the roof subsidence, the more likely the end face roof leaks. Therefore, the end face roof is extremely unstable during roof weighting, and it is necessary to pay attention to the influence of roof weighting on end face roof.

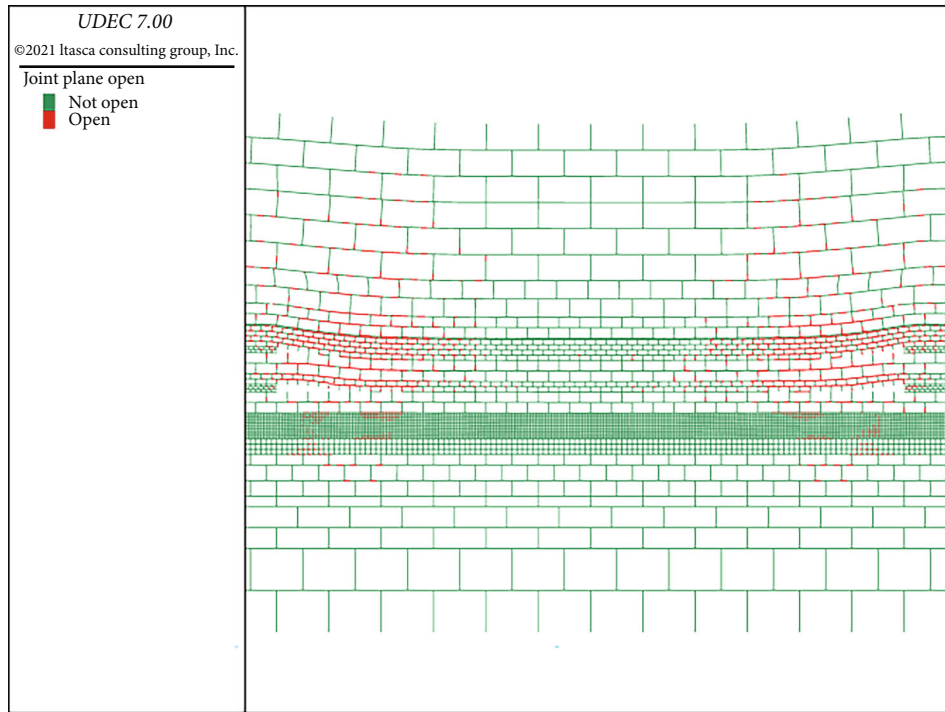
**5.5. Stress Variation of End Face Roof in 17# Coal Seam Mining.** Figure 20 shows the stress change of the end face roof under different calculation steps. It can be seen from Figure 20 that the stress of the end face roof increases with the increase of the advancing distance. When the advancing distance exceeds 50 m, the end face roof stress suddenly increases, indicating that the end face roof stress is large during roof weighting, and the end face roof leakage occurs. When the advancing distance is 70 m, the roof stress decreases and the end face roof is relatively stable. It shows

that roof weighting has influence on the stability of end face roof. Therefore, it is necessary to pay attention to the influence of roof weighting on end face roof.

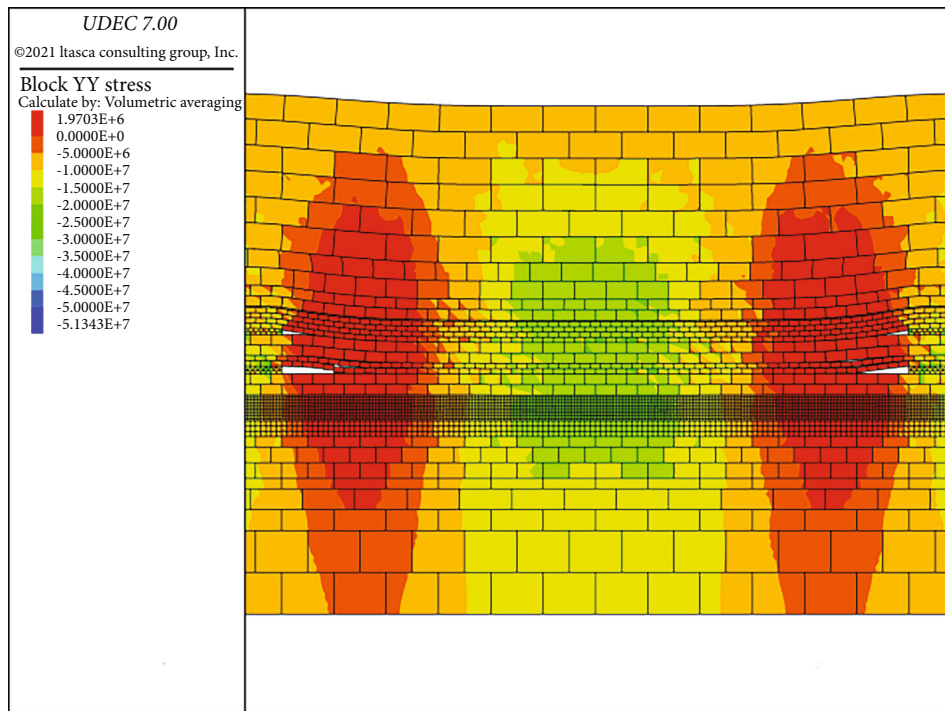
## 6. Prevention Measures of End Face Roof Leaks under Repeated Mining

Under normal conditions, the end-face roof fall and support crushing accidents in the working face are due to the insufficient support force, which cannot control the movement of key blocks. In terms of the working face mining under repeated mining of close-distance coal seams, the support force can control the movement of the broken block in the key layer, but the control of the broken end face roof cannot simply improve the working resistance of the support to prevent the occurrence of accidents according to the conventional practice. The end-face roof fall accident of working face 17101 in the mining stage is the inevitable result of the combined action of various influencing factors under certain circumstances. Therefore, the corresponding prevention should be carried out from the causes of end-face roof fall and the overlying strata movement law. Accordingly, the following prevention countermeasures are formulated [5, 23, 26, 31–33].

- (1) Reasonable control of tip-to-face distance reduces the exposure time and area of unsupported area.



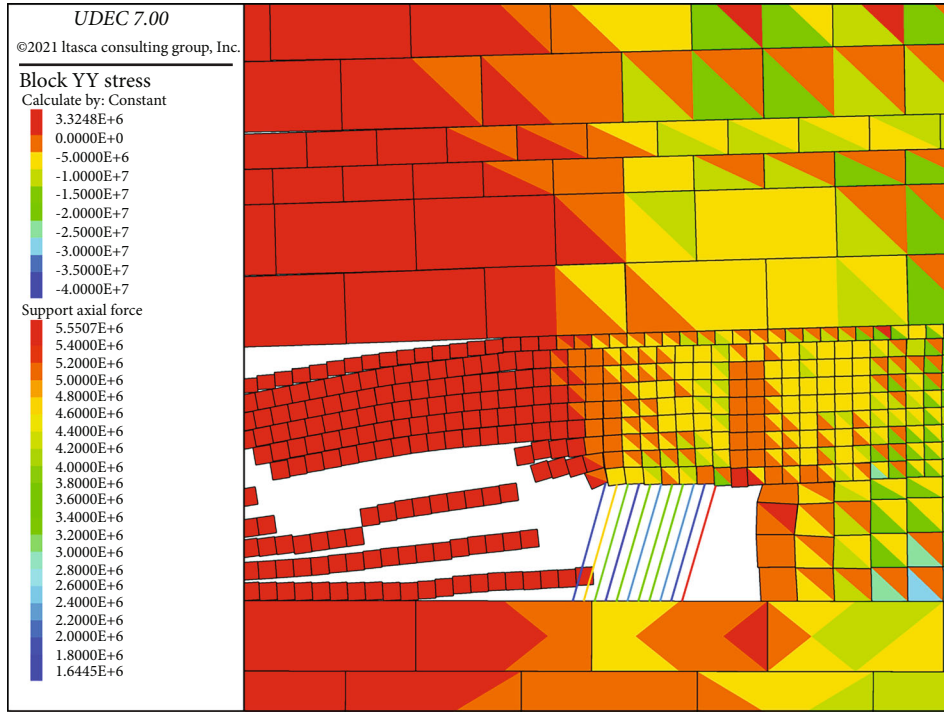
(a) Fracture diagram under repeated mining



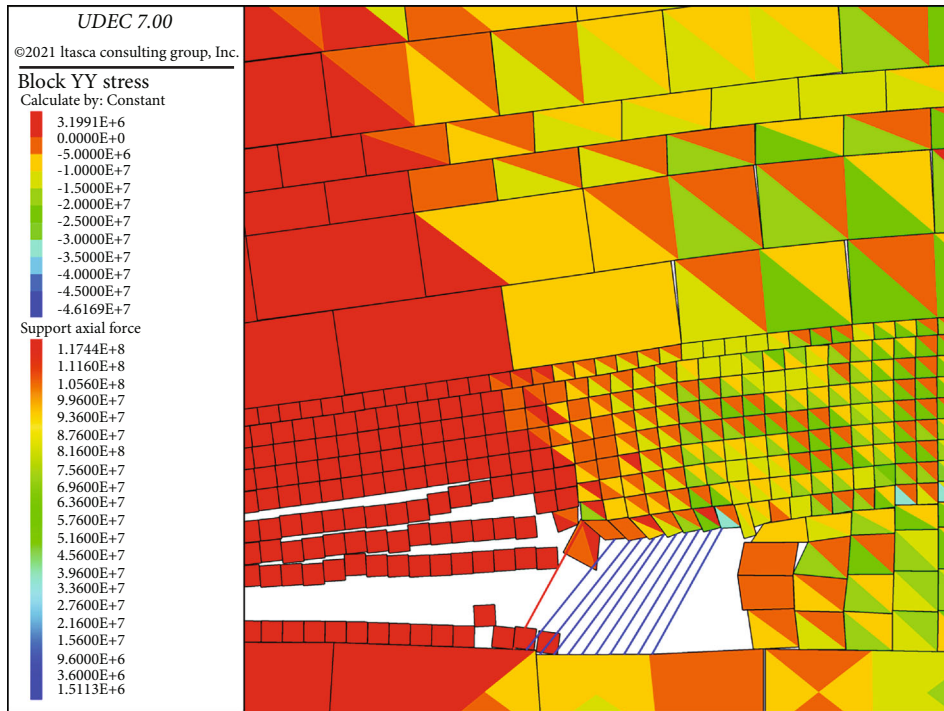
(b) Stress evolution diagram under repeated mining

FIGURE 17: Fracture-stress evolution after mining of 15# and 16# coal seams.

- (2) The initial support force should be appropriately increased for the broken roof area, and the advancing speed of the working face should be accelerated for the difficult control area
- (3) The roof activity law of fully mechanized working face under repeated mining is monitored, and the possible roof fall risks are predicted, and then, corresponding control measures are taken
- (4) Strictly control the working quality of the shearer to prevent the uneven coal cutting of the shearer,

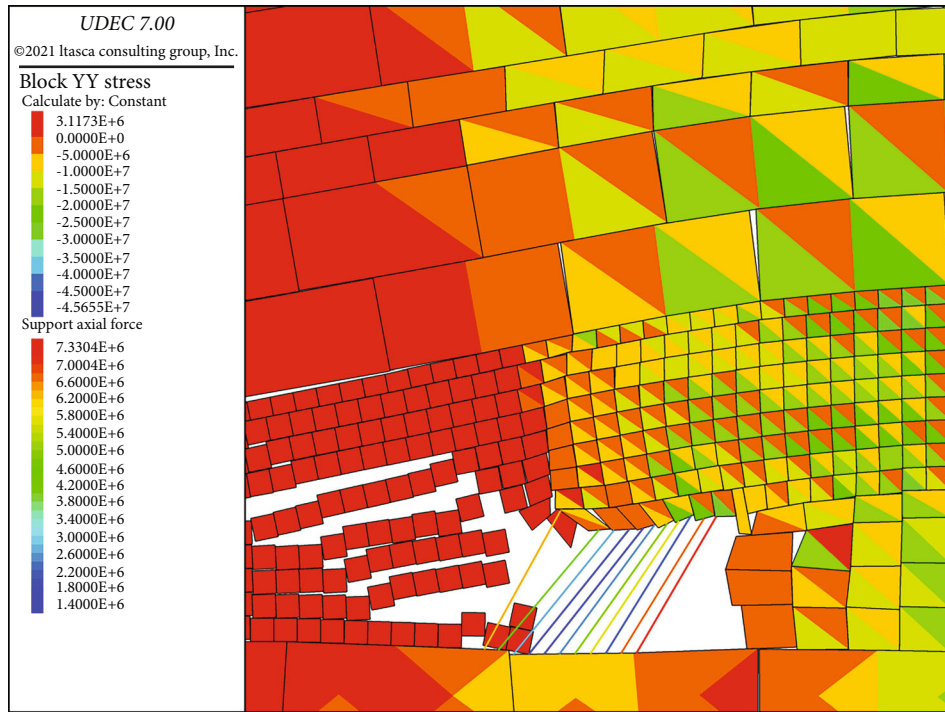


(a) 20 m

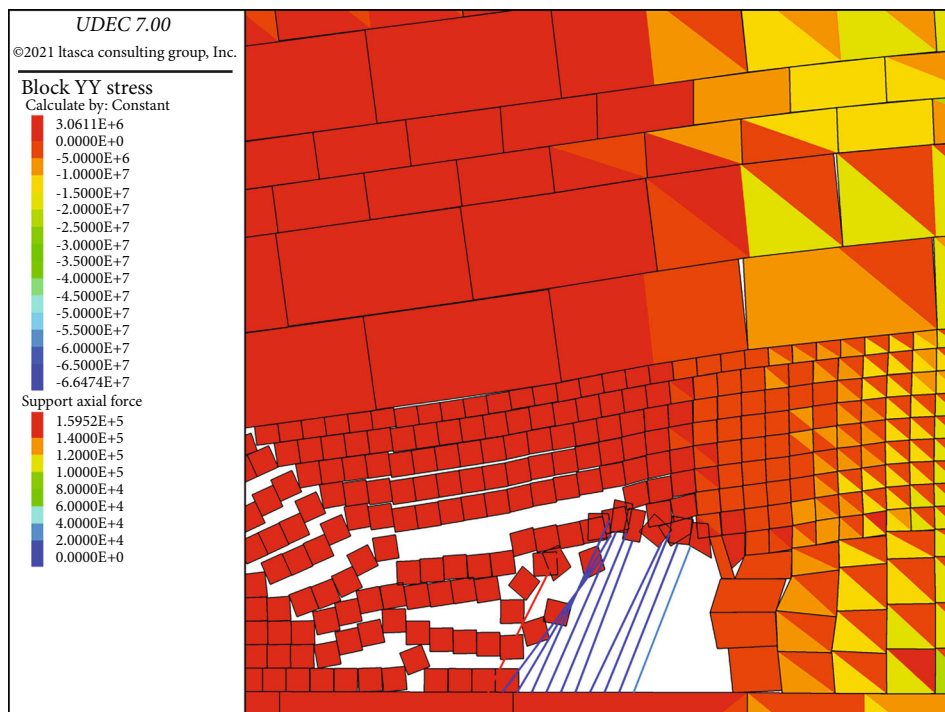


(b) 30 m

FIGURE 18: Continued.

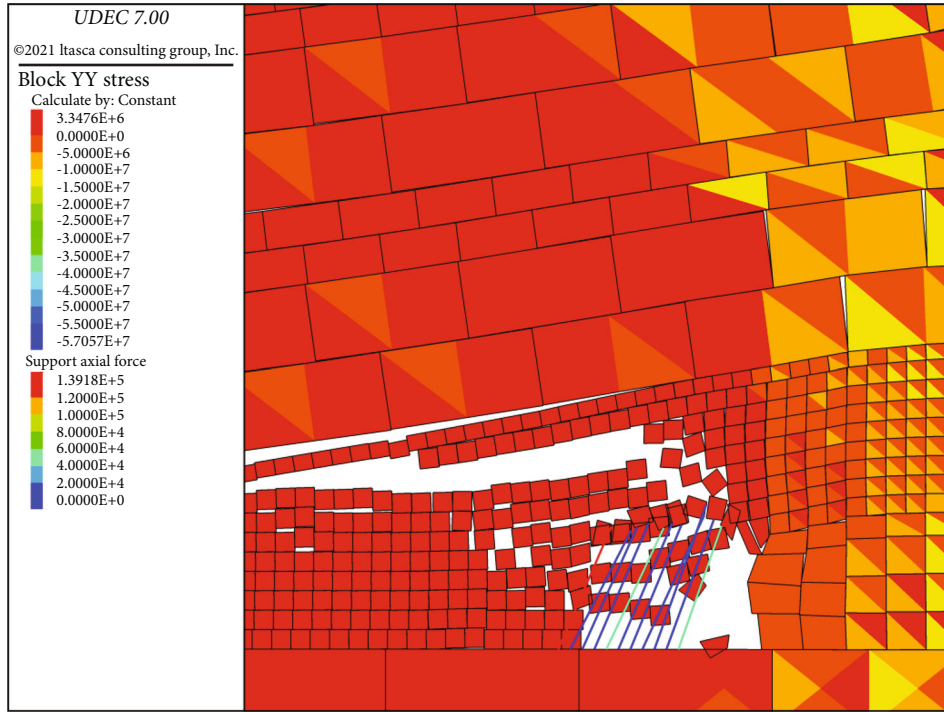


(c) 40 m

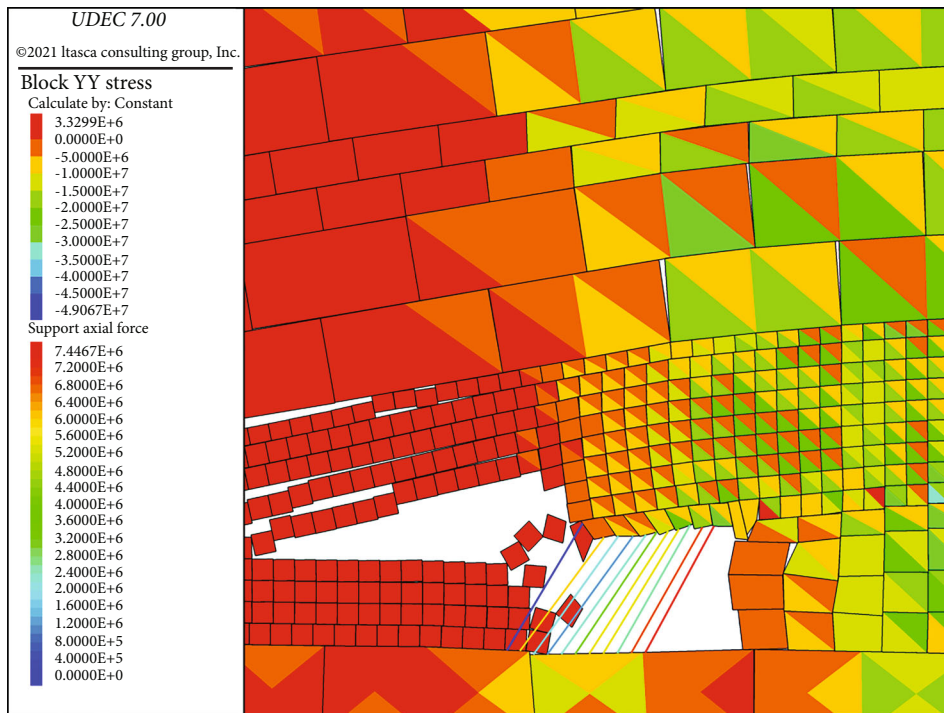


(d) 50 m

FIGURE 18: Continued.



(e) 60 m



(f) 70 m

FIGURE 18: Stability of end face roof under different advancing distances.

- resulting in the support and the roof can not be fully contacted.
- (5) Keeping the support in good working condition, the top beam shall not work with “head down,” and the elevation angle shall not exceed 5°, and the pressure shifting method is adopted
  - (6) In the section where the roof of the working face is seriously broken, grouting is used to solidify the end face roof, so as to improve the roof integrity
- In order to avoid the recurrence of roof fall accident, the working face 17101 roof is effectively controlled by taking the above measures in the mining process. Based on the

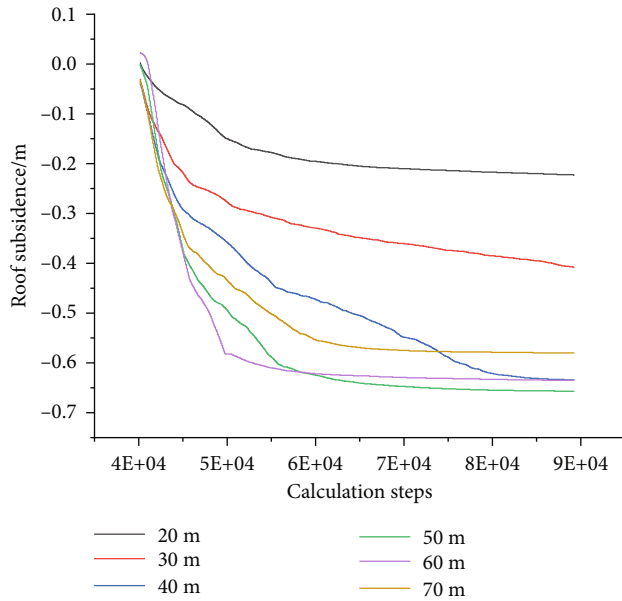


FIGURE 19: Roof subsidence at different calculation steps.

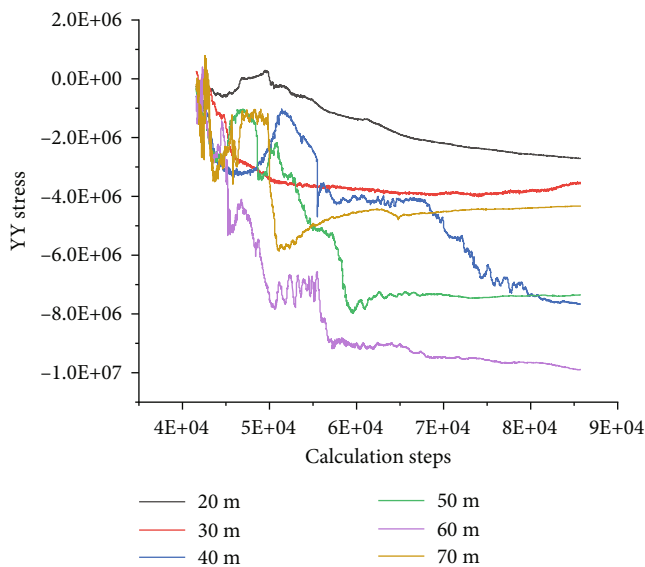


FIGURE 20: Stress changes of end face roof under different calculation steps.

above prevention measures, the subsequent mining of multiple working faces is safe and fast, which verifies the effectiveness of the control measures for the stope roof instability under repeated mining.

### 7. Conclusions

- (1) Similar simulation was used to analyze the movement characteristics of end face roof of fully mechanized working face under repeated mining in close-distance coal seams. It was obtained that the roof movement under repeated mining was divided into

four stages: normal mining, roof deterioration, end face roof leaks, and support crushing. The reasons affecting end face roof leaks and support crushing were obtained through the analysis of the four stages. The tip-to-face distance, support height, support state, and support initial support force were the main influencing factors in end face roof control. The main reason for the support crushing is that the roof above the support is broken, the main roof cannot form the self-stable structure, and the support force is insufficient

- (2) The numerical simulation is used to analyze the stability of the end face roof under different advancing distances in the lower coal seam mining of the close-distance coal seams. It is concluded that during the weighting of the working face, the dynamic load of the roof is large, the end face roof subsidence is large, and the roof caving phenomenon is easy to occur. Moreover, the roof weighting is frequent under repeated mining, resulting in the roof crushing, which makes the support unable to sustain, resulting in the support crushing accident
- (3) Through the analysis of numerical simulation and similar simulation experiment, the prevention and control measures of roof caving under repeated mining are put forward, the tip-to-face distance is reasonably controlled, the advancing speed of the working face is accelerated, and the roof activity law of the fully mechanized mining face is monitored under repeated mining. The shearer must cut the roof and clean up the coal on the support top beam in time. The support should have a good working state, and the end face roof of grouting curing is adopted. By taking the above measures, the roof of working face 17101 is effectively controlled

### Data Availability

All data, models, and code generated or used during the study appear in the submitted article.

### Conflicts of Interest

The authors declare that they have no conflicts of interest.

### Acknowledgments

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