



Numerical simulation and experimental study on floor failure mechanism of typical working face in thick coal seam in Chenghe mining area of Weibei, China

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Abstract

The hydrogeological conditions of Weibei coalfield in China are complex; the main mining No. 5 coal seam is seriously threatened by Ordovician limestone karst water disaster at the bottom of coal measures. Chenghe No. 2 Mine is a typical example. With the increase of mining depth, confined water pressure increases year by year. To find out the law of floor deformation and failure caused by No. 5 coal seam mining in Chenghe No. 2 Coal Mine, this paper takes 24,508 working face of Chenghe No. 2 Coal Mine as engineering geological background, and carries out research by numerical simulation and field test methods. The stress field, displacement field distribution law and plastic zone evolution characteristics of No. 5 coal seam roof and floor varying with the advancing degree of mining face are obtained by simulation calculation. The progressive failure process of the whole floor stratum is reproduced dynamically, and the development height of the water conducting fracture zone of overburden is given. The maximum failure depth of the floor occurs at the mining distance of about 1.5 times the mining width, at which time “the saddle shape” supporting pressure arch reaches its maximum. At the same time, the multi-point separated layer displacement meter is used to carry out field measurements. The results show that the maximum failure depth of floor occurs in the goaf, and the maximum range of the relative displacement of the floor is 8.0–8.5 m, which is close to – 6.1 m from the coal mining surface, consistent with the results of the numerical simulation. Comprehensive analysis shows that the maximum failure depth of coal seam floor in Chenghe No. 2 Coal Mine is 8.3 m. The conclusion provides a favorable basis for the rational formulation of water disaster control countermeasures. It provides reference and experience for mining under safe water pressure of aquifuge for prevention and cure water of similar working face in Chenghe mining area in the future.

Keywords Chenghe mining area · No. 5 coal seam · Mining under safe water pressure of aquifer · Floor failure depth · Numerical simulation

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Introduction

Since 1986, geological and hydrogeological investigation, comprehensive geophysical exploration of well top and bottom, chemical prospecting, the drilling exploration, overflow test and so on have been carried out in Chenghe mining area. A preliminary understanding of the hydrogeological conditions of three pairs of production mines (Chenghe No. 2 Mine, Quanjiahe Mine and Dongjiahe Mine) in the western part of Chenghe mining area was formed. At the same time, the floor failure depth test of No. 5 coal working face of Quanjiahe Coal Mine was carried out, but no similar test has been carried out for other mines in Chenghe Coal Mine. Moreover, in Chenghe mining area, the hydrogeological work in the exploration stage is less, the hydrogeological conditions in the mining area have not been thoroughly investigated and the mining depth, coal seam thickness, lithology of roof and floor, water bursting coefficient and other conditions of each mine are different; for other coal seam floor failure depth design reference basis is less. With increasingly high comprehensive mining intensity of the coal resources and wider mining width of the mining area, the depth of the mine in the Chenghe mining area continues to extend, and the threat of water inrush from the floor is more serious. The study of floor damage depth in Chenghe mining area is of great significance in both theory and practice. So, in this paper, numerical simulation and field test study on floor failure depth are carried out for No. 5 coal seam of Chenghe No. 2 Coal Mine in Chenghe mining area.

In the aspect of numerical simulation, Li (2012) used the stress coupling analysis system of seepage in the rock damage and fracture process to establish the numerical model of floor rock structure of No. 5 coal seam in Dongjiahe Coal Mine under the coupling effect of seepage field and stress field. The numerical simulation analysis of the influence of floor mining stress and seepage flow was carried out, and the mining failure characteristics, stress distribution and seepage characteristics of seam floor aquifuge were revealed. It has the guiding significance to analyze the law of water inrush from the floor of No. 5 coal seam in Dongjiahe Coal Mine (Li 2014). To study the evolution law of floor fracture and water inrush caused by stress, damage and seepage in the mining process, Lu and Wang (2015) used the numerical simulation method to reproduce the stress distribution, evolution of acoustic emission, characteristics of fracture development and the formation process of water inrush passage. It has application value of assessing the water inrush disaster of the floor plate in practice (Guo et al. 2017; Liu et al. 2018a; Yin et al. 2019; Chi et al. 2019). Yin et al. (2016) taking 4196 working face as engineering background and using

RFPA software to analyze the shear stress field, damage field and seepage field of the floor during coal seam mining. It simulated and reproduced the whole process of the formation of the floor slab from rupture to water diversion fissure channel. Li et al. (2013) have carried out relevant research on the depth of floor mining failure caused by No. 5 coal seam in Dongjiahe Coal Mine. By combining theoretical analysis and numerical simulation, the progressive failure process of the whole floor strata was dynamically reproduced (Gu and Li 2011). The maximum failure depth of the bottom rock is 10–11 m, and the results are consistent with the field measurements. Zhai et al. (2016), to explore the barrier effect of different rock strata combination floor to confined water, took the coal floor of the lower formation of Huaibei mining area as the research object, based on the FISH language to carry out the secondary development of the FLAC^{3D} software. The mining stress and the permeability of the surrounding rock of different combined characteristics were analyzed comprehensively under the condition of convection-solid coupling (Guo et al. 2017). Based on the mining background of No. 5 coal seam of Taiyuan Formation in Chenghe mining area, Li et al. (2015) used FLAC^{3D} analysis software to establish numerical calculation and analysis models under different working face width and coal seam burial depth, obtained the maximum floor failure depth corresponding to different parameters. They obtained the critical width fitting formula of No. 5 coal seam in Chenghe mining area under the condition of two factors by using the MATLAB software fitting analysis method. Liu et al. (2017a) studied the delayed water inrush process of hidden faults in coal seam floor by means of the FLAC^{3D} simulation analysis method, and put forward the formation law of potential water inrush passage under the influence of time effect. The results are in good agreement with the actual situation in the field (Meng et al. 2018; Sun et al. 2018; Zhang et al. 2017). Liu et al. (2017b) used RFPA software to study the mechanism of water inrush in the soft rock floor of coal mine. The stress field, seepage field and acoustic emission evolution process of water inrush path of coal seam floor were analyzed. The results can provide the theoretical basis and methodological guidance for the study of the water inrush mechanism of the coal seam floor and the prevention of mine water inrush accidents (Zhu et al. 2018).

In the practical observation of floor, Li (2015) used theoretical analysis and numerical calculation method to reinforce and rebuild the floor slab of No. 5 coal seam of Dongjiahe Coal Mine. Li realized the safe mining of the working face, better economic and social benefits and valuable experience for prediction and prevention of Ordovician limestone karst water hazard in the bottom floor of No. 5 coal seam of Taiyuan formation in Dongjiahe Coal Mine and Chenghe Mining area in the future. Xiao et al. (2001)

combined thick seam stratified mining with the observation method of seam floor movement and obtained the movement and deformation law of seam floor rock in stratified mining (Zhang et al. 2016; Liang et al. 2019). Li et al. (2018b) applied the theory of water inrush coefficient to put forward the zoning criterion of water inrush danger for the floor of No. 5 coal seam in Taiyuan Formation of this mining area, and divided the zoning of water inrush in the floor of No. 5 coal seam under two working conditions. They predicted the water inrush situation in the future mining conditions of the mining area and liberated the coal reserves threatened by water inrush of Ordovician ash (Li and Li 2016; Liu et al. 2018b).

At present, carrying out the on-site monitoring and improvement of floor and Ordovician strata of No. 5 coal seam in Chenghe Coal Mine is still in the developing stage (Li et al. 2018a, b). There are few cases of field measurement in China, and a complete technical system has not yet been formed. The reason is still the lack of theoretical support, and production practice and theoretical research are disjointed. At present, there are few research results on the mining failure depth of the No. 5 coal seam floor in Chenghe No. 2 Coal Mine. Therefore, in this article, to find out the deformation and failure law of the bottom plate caused by coal seam mining, the 24,508 working face of Chenghe No. 2 Coal Mine are used as the engineering geological background. The model was constructed by numerical simulation, and the damage law of the top and bottom plates of No. 5 coal seam under the influence of mining was obtained, which was consistent with the field test results. The result provides a favorable basis for the pressure mining and the rational formulation of water damage prevention measures for similar working faces in the Chenghe mining area.

Study area

Location

Chenghe No. 2 Mineral is located at Shigou Village, Yaotou Town, Chengcheng County, Shaanxi Province, in southwest (orientation 236°) of Chengcheng County with a straight-line distance of 6 km and road distance of 10 km (Fig. 1). Chenghe No. 2 Mineral is situated in the west of the Chenghe mining area. Its stratum system is close to neighboring Dongjiahe and Quanjiahe coal mines. Its bedrock is mainly exposed to Majiagou, two sides of the Yuzihe-Yaotougou ravine, and both sides of Luohe River, and the other section within the mineral rights range is covered by loess. Chenghe No. 2 Mineral lies in Weibei loess plateau gully region where the terrain is full of ups and downs, and ravines and gullies crisscross. The terrain within this area is high in the north and low in the south, with

a relative height difference of 150–200 m, with 500–689 m above sea level.

Working face basic situation

The numerical simulation and field test were carried out in 24,508 working face of No. 5 Coal seam in Chenghe No. 2 Coal Mine. This working face is located in the north of the second level and fourth mining area, and is surrounded by real areas. The west end is connected with the belt downhill and track downhill of the fourth mining area. The burial depth of the working face is about 400 m, the inclined length of the working face is 60 m, and the near horizontal coal seam is mined. The main water-filling factors of 24,508 working face are the fissure water of the roof sandstone group and Ordovician water below the bottom plate. The fissure water of the roof sandstone group is mainly the fissure water in K_4 , K_{mid} , K_5 and sandstone, which is introduced into the workpiece surface through the overburden strata roof water conductive fissure zone. The working face is located in the Carboniferous Taiyuan formation on the top of the Taiyuan Group with a thickness of 3.85–4.29 m and an average thickness of 4.0 m. The bottom plate is mostly siltstone and sandy mudstone. The 24,508 working face is a confined mining area, the distance between No. 5 coal seam and the top of Ordovician ash is 25–45 m, and the relative water pressure of the aquifuge is 0.81–0.86 MPa. Both air return way and intake airflow roadways are supported by I-shaped steel sheds, adopting the combined support form of anchor, mesh, cable and beam, and the working face is arranged along the long wall. The comprehensive mechanized coal mining method is adopted in the 24,508 working face to control the roof by the full height collapse method for one-tine mining with long wall retrogression.

Working face lithological division

According to the actual lithology of typical drilled columnar strata selected from 24,508 working face, the overlying rock mass is divided into 11 layer model materials according to the similarity of engineering geological properties. From top to bottom, there are overlying rock, medium-grained sandstone, carbonaceous mudstone, No. 5 coal seam, siltstone, sandy mudstone, quartz sandstone, K2 limestone, No. 10 coal seam, aluminous mudstone and Ordovician limestone. The mechanical parameters and rock quality indexes of the roof and floor plates of 24,508 working face are shown in Table 1.

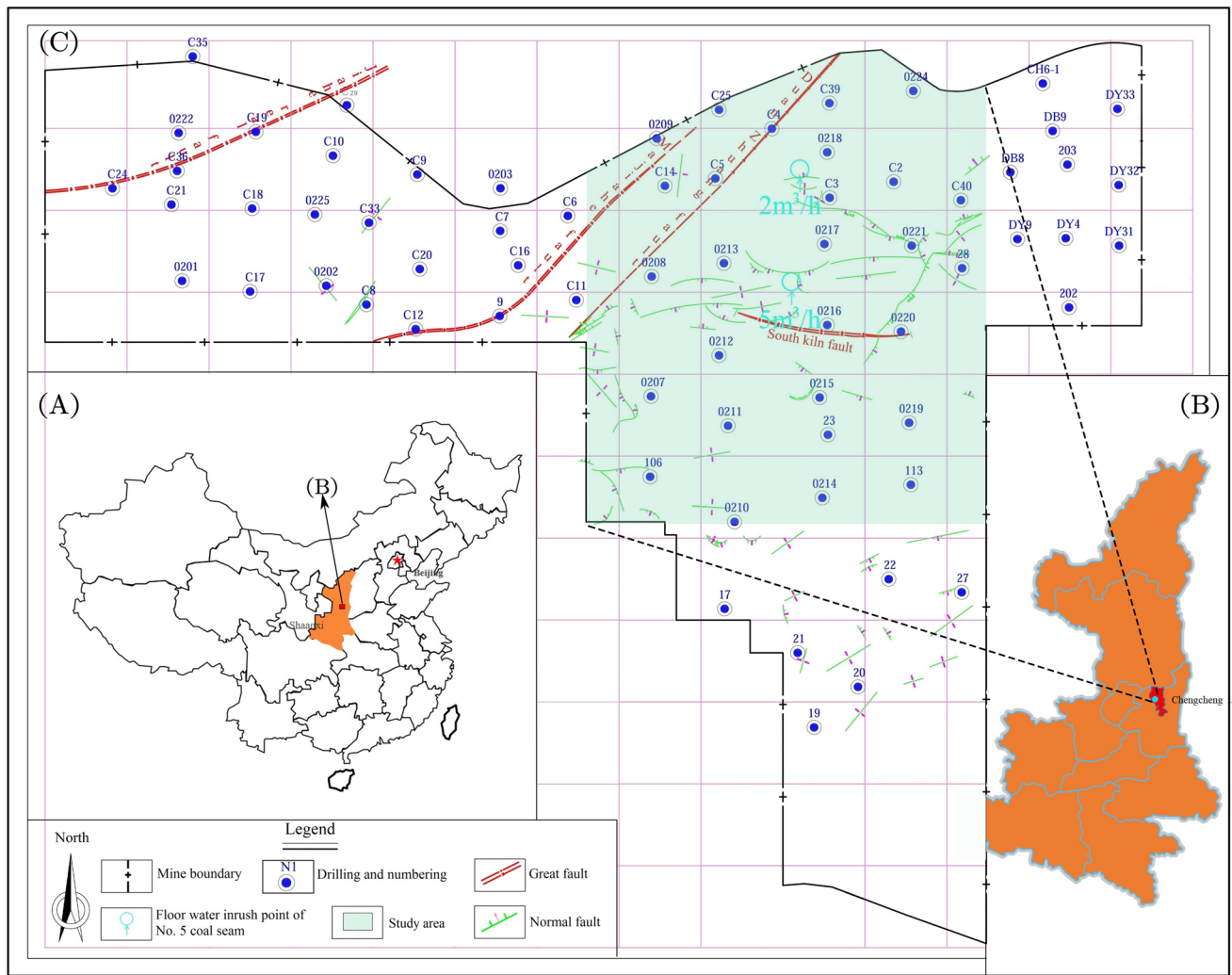


Fig. 1 Location and study area

Table 1 Rock mass parameters of roof and floor plates in 24,508 working face

Lithology	Volume modulus (GPa)	Shear modulus (GPa)	Density (kg/m ³)	Cohesive (MPa)	Internal friction angle (°)	Tensile strength (MPa)	Rock quality designation (%)
Overlying rock	4.67	4.34	2670	4.67	39	1.34	–
Medium grain sandstone	3.38	3.32	2650	5.00	40	1.10	49
Carbonaceous mudstone	3.57	3.41	2630	3.84	35	1.04	32
No. 5 coal seam	1.43	0.44	1400	1.82	35	0.10	51
Siltstone	4.22	4.03	2620	3.98	39	1.11	60
Sandy mudstone	4.23	4.52	2640	4.12	37	1.23	39
Quartz sandstone	4.54	4.31	2660	4.72	40	1.21	66
K2 limestone	8.97	5.65	2760	4.01	38	1.79	84
No. 10 coal seam	1.43	0.44	1400	1.00	25	0.10	43
Aluminous mudstone	4.86	4.78	2620	4.71	30	1.51	38
Ordovician limestone	8.78	5.23	2770	4.32	37	1.32	77

Numerical simulation and field test

Numerical simulation technique

The numerical simulation method FLAC^{3D} is used to analyze the disturbance and failure effect of roof and floor plates caused by 24,508 working face mining in No. 5 coal seam of Chenghe No. 2 Coal Mine. It is relatively easier to construct and simplify the model, with fewer parameters and relative simplicity.

The establishment of the model

This study takes 24,508 working face of No. 5 Coal seam in Chenghe No. 2 Coal Mine as the research object, simulates mining depth 400 m, working face mining width 60 m and coal seam mining thickness 4.0 m. In the near horizontal seam mining, the size of the model is 300 m × 200 m × 90 m in length, width and height. In the model, the bottom interfaces of vertical X-axis, vertical Y-axis and Z are all set as displacement boundaries, while the top interface is set as stress boundary, among them the vertical and bottom interfaces are set as rolling interfaces. The Ordovician limestone layer is partly regarded as aquiclude, which applies pressure on the Ordovician limestone head.

A three-dimensional numerical model is used to simulate the stress field in this calculation, and the failure of the rock mass is judged by the Mohr–Coulomb yield criteria. Simulating the displacement, stress and plastic failure of the mining face after the mining reaches equilibrium step

by step, the original rock stress is a static stress field and the rock formation is a continuous medium.

Boundary condition

In the process of numerical simulation of floor failure depth in Chenghe No. 2 Mine, the boundary conditions of the model should be determined first. Most of the existing numerical analysis methods are based on discretization, and the complex geotechnical engineering rock mass is discretized into smaller unit aggregates in the finite study area. The stress state is basically the same when mining coal under alluvium in North China Plain. In the plain area, the crustal stress in the area has a burial depth of 500 m, and the lateral pressure coefficient is generally 1.0–2.5. Therefore, the lateral pressure coefficient is 1.1 in the numerical simulation of the floor failure depth.

Simulated excavation

In this FLAC^{3D} numerical model, the geological model is established and each element parameter is given, while the balance of each node and element should be obtained. Only after the geological model is balanced can excavation calculation be carried out. General stress balance mainly looks at vertical stress, as shown in Fig. 2. The thickness of the coal seam in the figure is 4.0 m. The excavation started at 70 m at the open-off cut from the lower boundary, and the water pressure at the top of the Ordovician limestone interface was 0.84 MPa. During the excavation, the excavation distance is set to 210 m, which is 3.5 times that of the mining width.

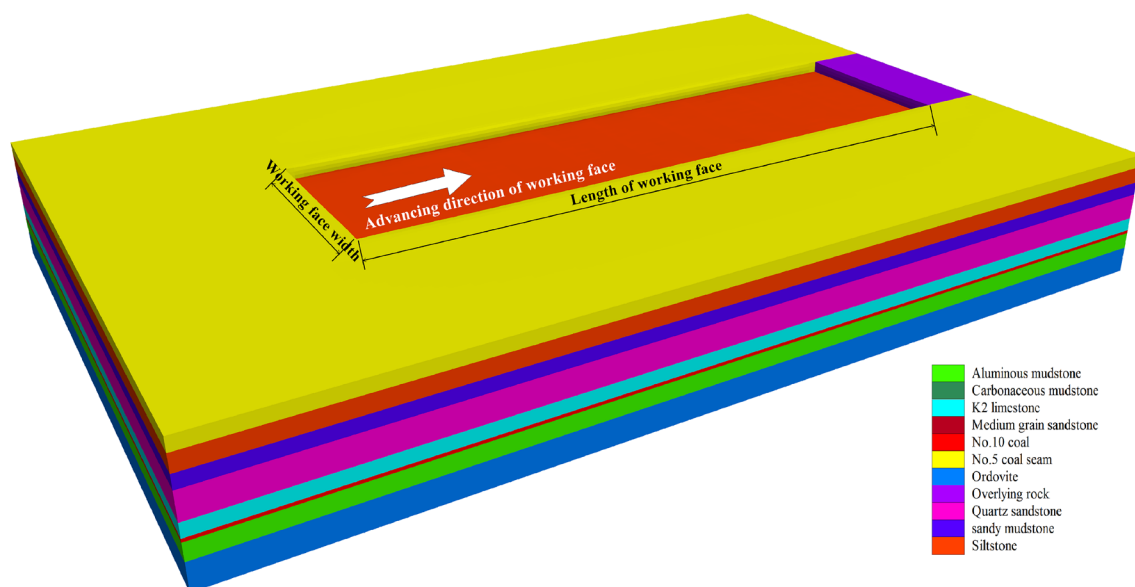


Fig. 2 Stope layout plan

Mining from coal seam openings, with each excavation 10 m and a total of 21 excavation steps, combined with the actual mining situation of 24,508 working face, goaf overlying strata can achieve full mining state.

According to the requirement, the calculation model of 24,508 working face in No. 5 coal seam of Chenghe No. 2 Coal Mine is established. The calculation results are compared and analyzed, and the relevant laws are obtained. The evolution law of roof and floor plates displacement, the stress evolution law of surrounding rock and the distribution law of plastic zone of coal seam roof and floor in the mining process of 24,508 working face are simulated and deduced. The relationship curves between the height of plastic failure of the overlying strata and the depth of floor mining failure with the mining distance of working face are obtained.

Field test

Test scheme for testing the failure depth of the floor plate

In this paper, based on the engineering background of No. 24,508 working face in Chenghe No. 2 Coal Mine, a field monitoring study on the depth of floor mining failure can be carried out, which can be used to monitor the failure depth of floor rock formation on the spot. Thus, the

distribution law of floor failure depth of No. 5 coal stope is determined to achieve the intended purpose. In this paper, one observation line is arranged for data monitoring during the stoping period in No. 5 drilling ground of No. 5 air return way in 24,508 working face. The section layout for monitoring the depth of floor damage during mining in No. 5 drilling ground of 24,508 working face is shown in Fig. 3.

Drilling equipment and construction technology

Drilling equipment: select special underground pit penetration drilling MK-3 drilling machine.

Drilling tool combination: use $\phi 42$ internal drill pipe, $\phi 50$ diamond bit, plus anti-deviation centralizer, and maintain adequate drilling pressure.

Core drill bit: 75 × 1500 mm core barrel.

Flushing fluid: drilling with all-hole clear water.

One borehole was completed to test the floor fracture depth, and one borehole was completed to sample the floor core. Nearly, 20 samples were taken during the drilling process. The design inclination of the borehole was 90°, the depth of the final borehole was 10 m, and the final borehole was in the quartz sandstone horizon. The field diagram of drilling equipment is shown in Fig. 4.

Fig. 3 Section layout drawing of floor damage depth monitoring design in No. 5 drilling ground of air return way of 24,508 working face: **a** pre-mining stationing, **b** post-mining stationing

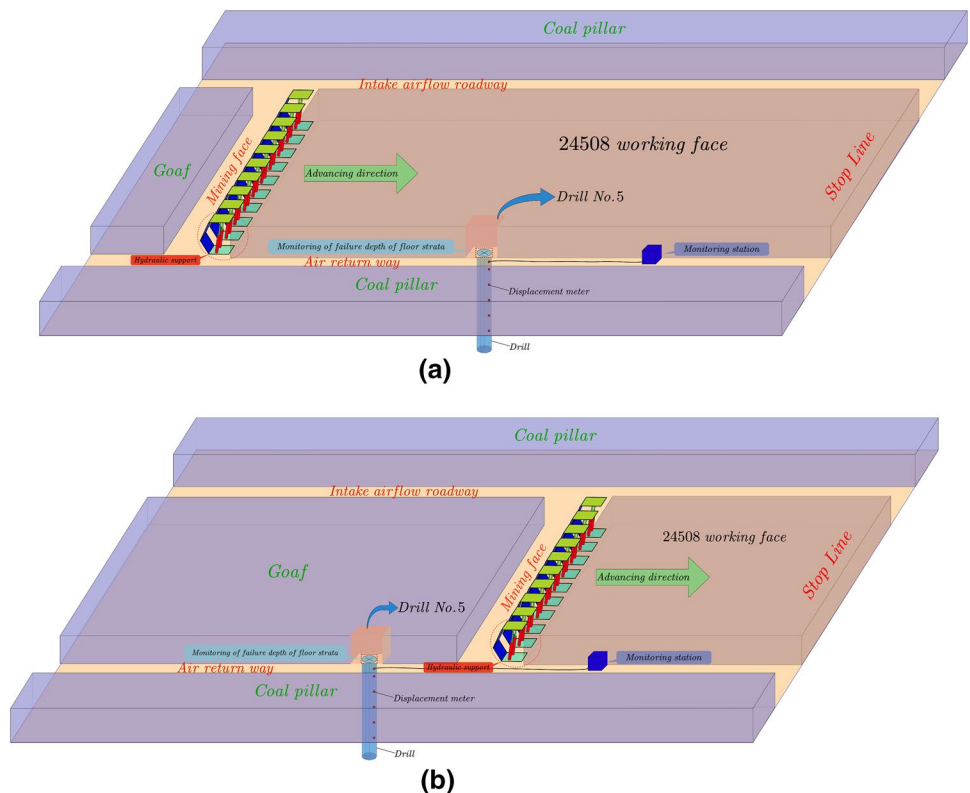




Fig. 4 Site map of drilling equipment

Testing time

The site construction and test process lasted 52 days. More than 40 observations were carried out in the borehole, and about 1000 sets of data were obtained.

Testing procedure

The testing process was carried out in the air return way drilling field of 2458 working face. The floor failure depth was monitored by 22-point separation displacement meter. The floor base point depth was 13 m, 12 m, 11 m, 10.5 m, 10 m, 9.5 m, 9 m, 8.5 m, 8 m, 7.5 m, 7 m, 6.5 m, 6 m, 5.5 m, 5 m, 4.5 m, 4 m, 3.5 m, 3 m, 2.5 m, 2 m and 1.5 m, respectively. The floor measuring points were arranged in the construction drilling field of the air return way of 24,508 working face. The monitoring site of floor failure depth is perpendicular to the bottom plate platform of the No. 5 drilling field. First, the shallow hole has diameter 75 mm and depth 1.5 m. The sleeve is inserted into the casing with outer diameter 75 mm, inner diameter more than 50 mm, length 1.5 m and concrete foundation reinforcement outside the casing. Then continue to drill deep holes with a diameter of 48 mm and a depth of 11.5 m. The total depth of the bottom drilling is 15 m, as shown in Fig. 5.

Results and analysis

Results analysis of numerical simulation

According to a certain step distance, the distribution law of roof and floor plastic zone, stress distribution law and displacement distribution law of five coal seams under the action of stress field and seepage field are simulated, respectively (in the three-dimensional simulation diagram of this chapter: the X direction represents the working face strike length in the model, that is, the direction of working face advance, and the Y direction represents the inclined length of the model, that is, the direction of working face inclination. The Z direction represents the height of the model). The distribution of the initial stress field (vertical stress) in the numerical model is shown in Fig. 6.

Analysis of the distribution of stress range of stope roof and floor

Figures 7 and 8 show the development rule diagram of vertical stress field of stope roof and floor of 24,508 working face in Chenghe No. 2 Coal Mine after backstopping in No. 5 coal seam (unit MPa in the figure, negative sign indicates pressure area).

From Figs. 7 and 8, we can see that: when the working face is pushed to 30 m, the roof and floor rock formation forms elliptical stress arch, the tensile stress zone appears overlying the strata above the goaf, the goaf directly roof collapses, and presents the shape of arch falling. While the goaf floor is in the mining and unloading area, the tensile stress zone is formed, and the direct bottom mudstone layer is gradually damaged by tension from top to bottom.

When the working face advances to $L = 60$ m, the elliptical stress arch increases and rises, showing a symmetrical distribution pattern. The supporting pressure zone is formed in the open-off cut and coal wall of the coal face and its above overlying strata, and the distribution range increases continuously. The supporting pressure area is formed in the coal wall rock body behind the open-off cut and the coal mining in the front and rear, and the distribution range of the supporting pressure on the inclined section plane of $X = 66$ m and $X = 122$ m in the middle of the goaf increases constantly. The the corresponding high stress region appears in the coal pillar on both sides of the coal pillar. Its value range is larger than the stress value which the coal body can bear. Further damage occurs near the edge of the coal pillar, the peak value of the supporting pressure extends to the deep part of the coal body, and the inner part of the goaf is a pressure reduction area (blue).

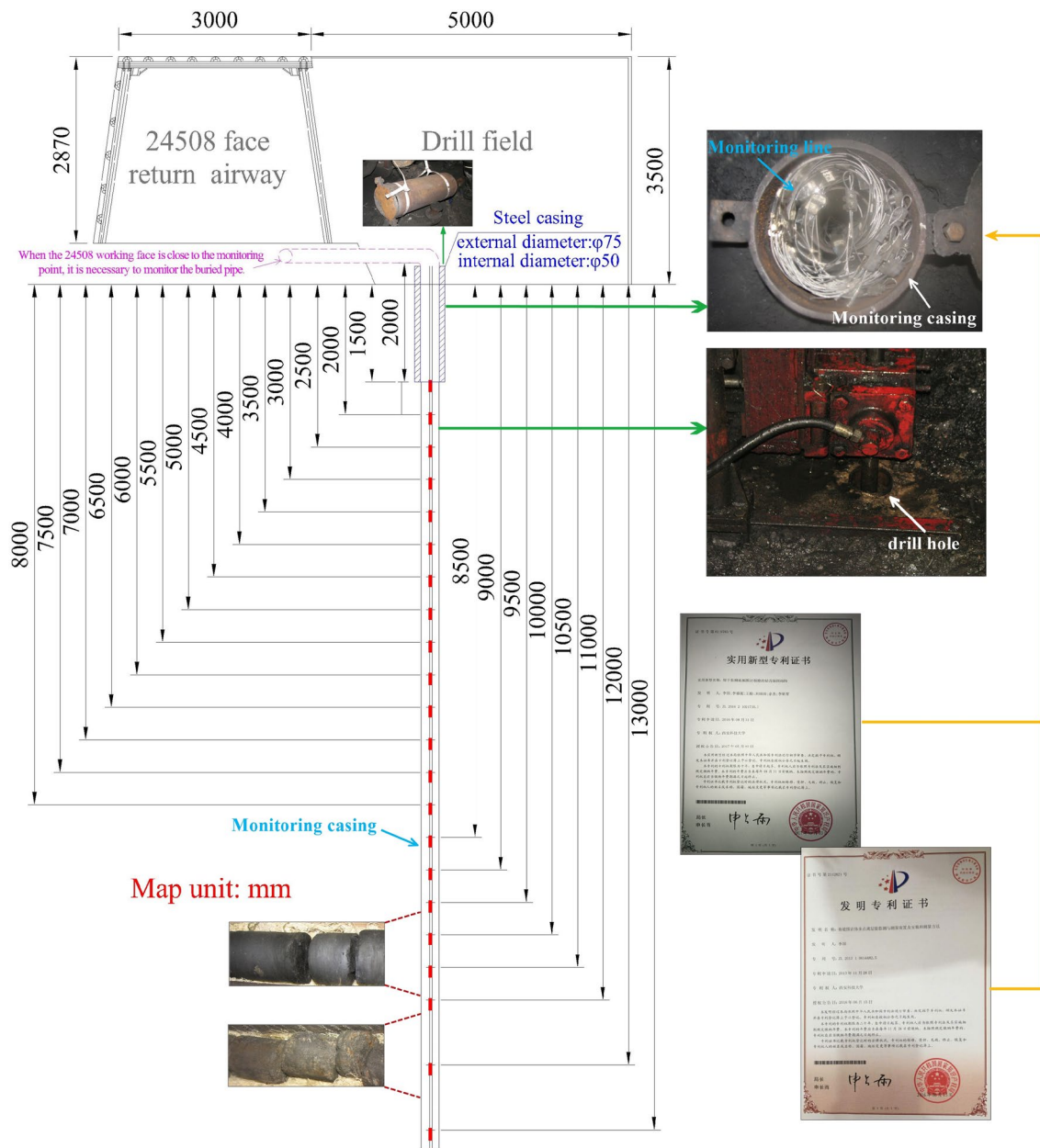


Fig. 5 Monitoring arrangement of damage depth of borehole floor in No. 5 drilling field of air return way of 24,508 working face (unit: mm in figure)

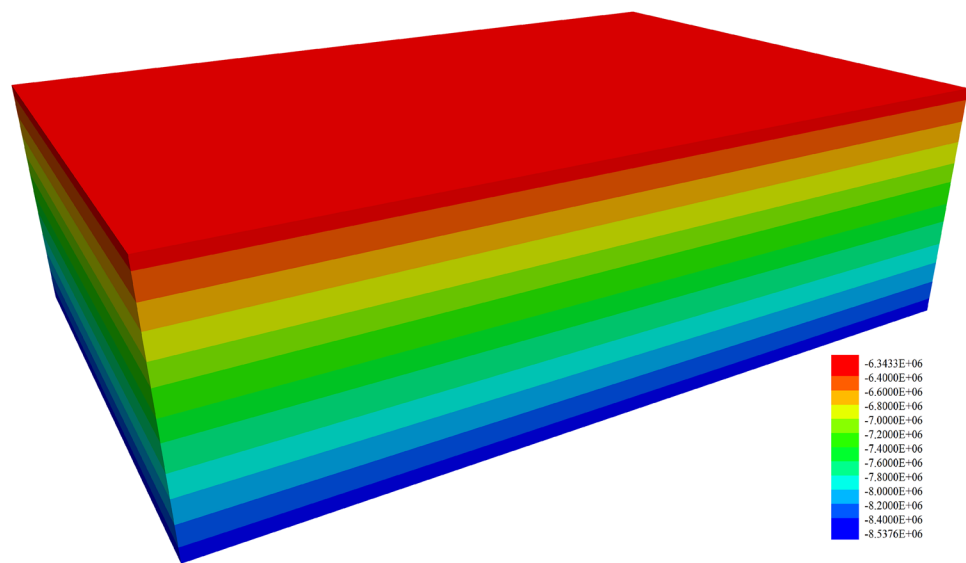
When the working face is pushed to $L = 90$ m, the distribution of supporting pressure on the inclined section plane of $X = 122$ m in the middle of goaf increases continuously; the variation of s_{zz} stress distribution on the $X = 66$ m inclined section plane is relatively small, which has little effect on this position. However, the phenomenon of s_{zz} stress rise begins to appear in the $X = 122$ m inclined section plane, which indicates that the advance bearing pressure has affected the position.

When the working face is pushed to $L = 110$ m, the coal seam is mined to $X = 178$ m, and the tensile stress of the

roof and floor plates in the middle of the goaf disappears in the section plane $X = 122$ m and $X = 66$ m, which indicates that the overlying strata completely collapses and the caved gangue almost completely fills the goaf. A smaller pressure arch which is not completely compacted is formed around the goaf, and the local tensile stress failure zone is formed.

When the working face is pushed to 130 m and 150 m, it can be seen on the $X = 178$ m profile that the stress s_{zz} of the roof and floor of the complete caving and compacting part of the gangue in the goaf is almost unchanged, which indicates that the goaf has been completely compacted by

Fig. 6 Initial stress field (vertical stress)



the carving gangue and bears the weight of the rock above it. On the section $X = 178$ m, the pressure of the roof and floor strata in goaf move forward with the continuous advance of the mining face, and the development height of water conduction fracture zone and the mining failure depth and scope of floor no longer change with the mining of the coal seam, which indicates that the goaf has entered a stable state at this time, and the development of plastic zone reaches its maximum value.

The working face continues to move forward to the 170–210 m interval. With the advancing of the mining face, the pressure stress of the bottom plate in the goaf gradually increases to a stable level, showing a small pressure arch shape above the open-off cut and the nearby goaf. Preserving the stable form is not affected by the mining of the coal seam, while the mining face and the goaf behind it present a periodic pressure arch change law as a whole with the mining of the coal seam. The height and range of the pressure arch move forward, but they are no longer widened and increased.

Analysis of the evolution law of displacement field of stope roof and floor

Figures 9 and 10 show the evolutionary map of the roof and floor displacement field after backstopping in No. 5 coal seam 24,508 working face of Chenghe No. 2 Coal Mine (unit cm, the negative sign in the figure represents vertical downward displacement).

It can be seen from Figs. 9 and 10 that the roof overlying strata in the inclined direction of the goaf $X = 10$ m, $X = 66$ m will gradually decrease with the development of the mining face when the working face advances $L = 30$ m and 60 m, respectively. With the backstopping of the mining

face, the direct roof caving and the old roof collapse, the fracture range of the rock formation above the goaf expands, the height of the gangue caving increases, and the maximum settlement of the roof increases gradually (in the blue area, the deeper the color, the bigger is the subsidence). The bottom plate is in the unloading state, and the bottom floor drum phenomenon occurs (the red area; the darker the color, the bigger is the bottom drum quantity). When the propulsion degree reaches 60 m, the roof subsidence value at the center of the goaf reaches 3.15 m, and the subsidence of the overlying strata above the goaf shows an inverted trapezoid shape. In contrast, the bottom floor at the center of the goaf is affected by the unloading of coal seam (red area), and the amount of floor drum increases from 0.38 to 0.62 m with the advance of the mining face. However, the increase rate is not as fast as the amount of roof subsidence. This is mainly because the floor is also increased by the amount of carving gangue.

When the working face is pushed to 90 m, the inner space of the goaf is gradually compacted, and the floor is subjected to the roof pressure of overlying rock besides the weight of the gangue. At this time, the maximum subsidence value of the top roof in the inclined direction $X = 122$ m is still occurring in the center of the goaf, reaching 3.46 m, and the floor bottom drum quantity is 0.64 m. With the continuous mining of coal seam, the subsidence of goaf in this section is no longer increased, which is caused by the recovery of pressure stress in goaf.

When the working face is pushed to 110 m, the working face has multiple periodic pressure. From the vertical stress field, it can be seen that the height of the pressure arch develops to the maximum, the goaf is gradually enriched and roofed by the carving gangue, and at this

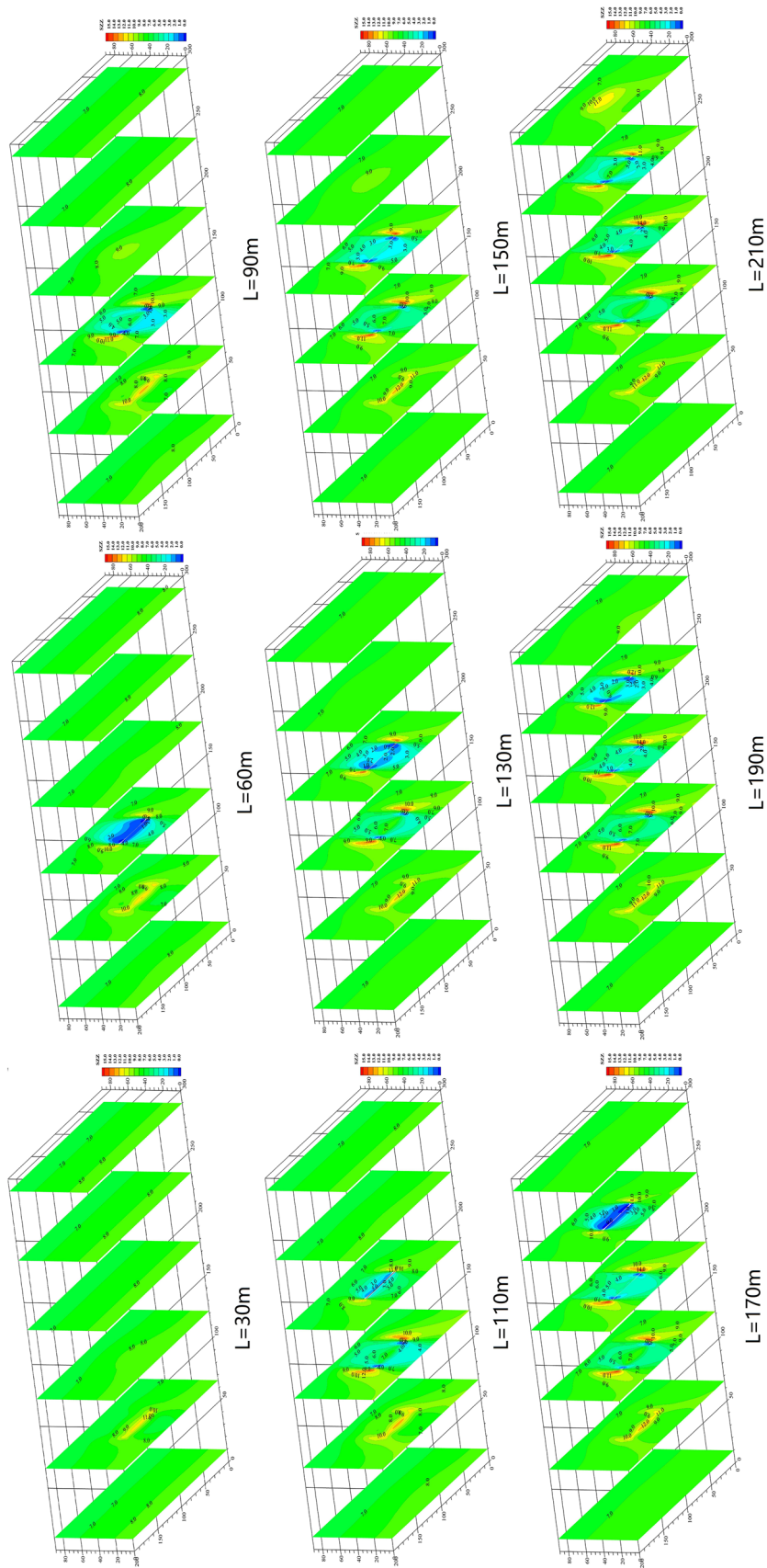


Fig. 7 3-D stress distribution law of stope roof and floor S_{zz} under different propulsions distance (L in the graph represents working face propulsions distance, and the unit in the graph is MPa)

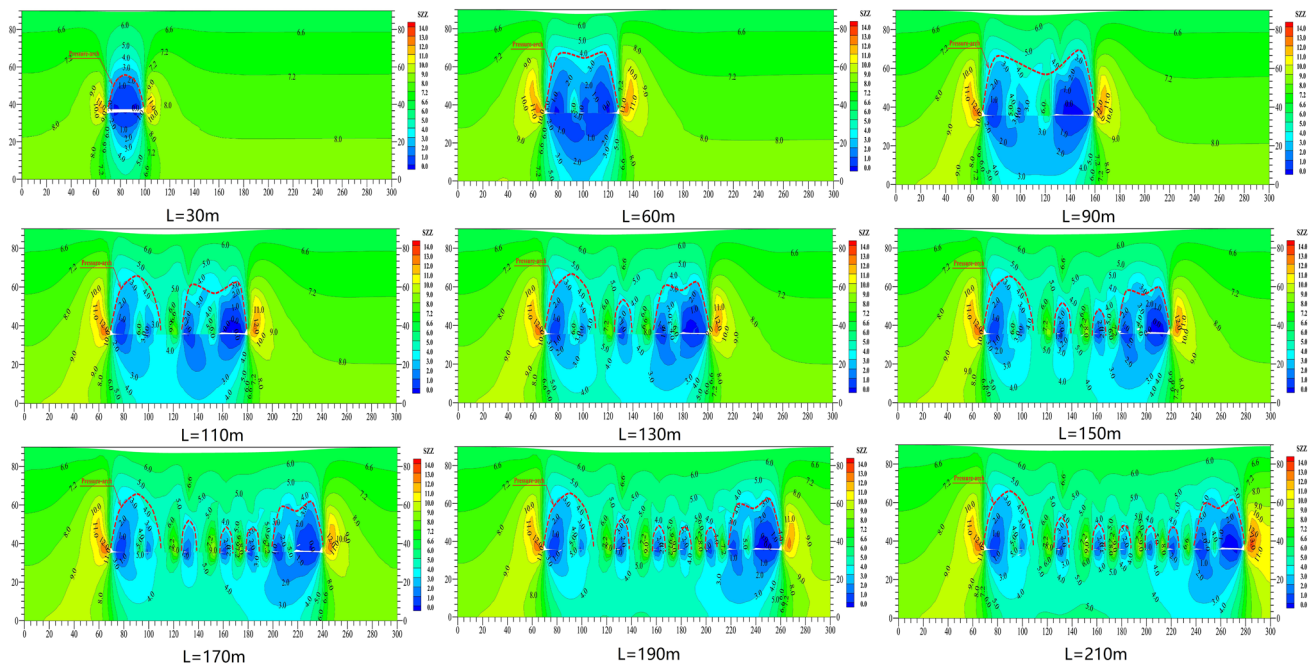


Fig. 8 Two-dimensional stress distribution law of stope roof and floor S_{zz} under different propulsive degree ($Y = 100$ m) (L in the graph represents working face propelling distance)

moment the roof subsidence reaches 3.46 m. It occurs on the $X = 122$ m section in the middle of the goaf.

After that, as the mining face gradually moved forward to 130 m, 170 m, 190 m and 210 m, within the pressure range of one to two cycle weighting range coming from the goaf immediately following the working face, the roof and floor space of the goaf again formed a small-scale pressure arch (Fig. 8, visible). After the mining face was pushed forward, the goaf in the rear gradually changed from pressure unloading to pressure recovery, and no change of displacement occurred after the bottom plate was connected to the roof. This rule goes on and on until the coal seam has been finished mining.

Distribution law of support pressure in coal seam floor

To directly reflect the evolution characteristics of supporting pressure in the front of the back coal wall and the goaf in front of the bottom plate and roof of No. 5 coal seam, the data of coal seam floor under different mining steps are extracted, as shown in Fig. 11 (unit: MPa in the figure). Figure 12 shows the distribution curve of supporting pressure in different positions of coal seam floor ($Y = 100$ m, 160 m, 190 m).

- (1) Distribution law of supporting pressure around the stope

As can be seen in Fig. 11, when the coal seam is mined, the weight of the overburden rock is distributed to the coal wall around the goaf. The support formed is redistributed and transferred to the surrounding coal mass and pillar, and the stress redistribution occurs on the coal wall around the goaf. Thus, a supporting pressure distribution band is formed (the brighter the red part of the diagram, the greater is the value of the supporting pressure). The leading supporting pressure moves forward with the advance of the working face, and the supporting pressure on the coal mass and pillar on both sides of the working face and on the side of the cutting hole. At this time, with the increase of mining length, more amount of gangue falls from the roof of the goaf. The space between the top of the caving gangue and the upper part of the rock is gradually reduced, and the upper non-falling strata are supported again in varying degrees. The amount of gangue falling from the overlying strata in the central part of the goaf is large, and the middle part of the spatial arch structure first touches the gangue. When the falling gangue clings to the roof and produces the interaction force, the goaf can be compacted. At this stage, the bottom plate of the goaf is subjected to the pressure of the overlying strata in a “wave shape”. The peak point of the small wave peak is the initial pressure and periodic pressure of the old roof in the field. As the mining surface continues to advance, the goaf is gradually filled with

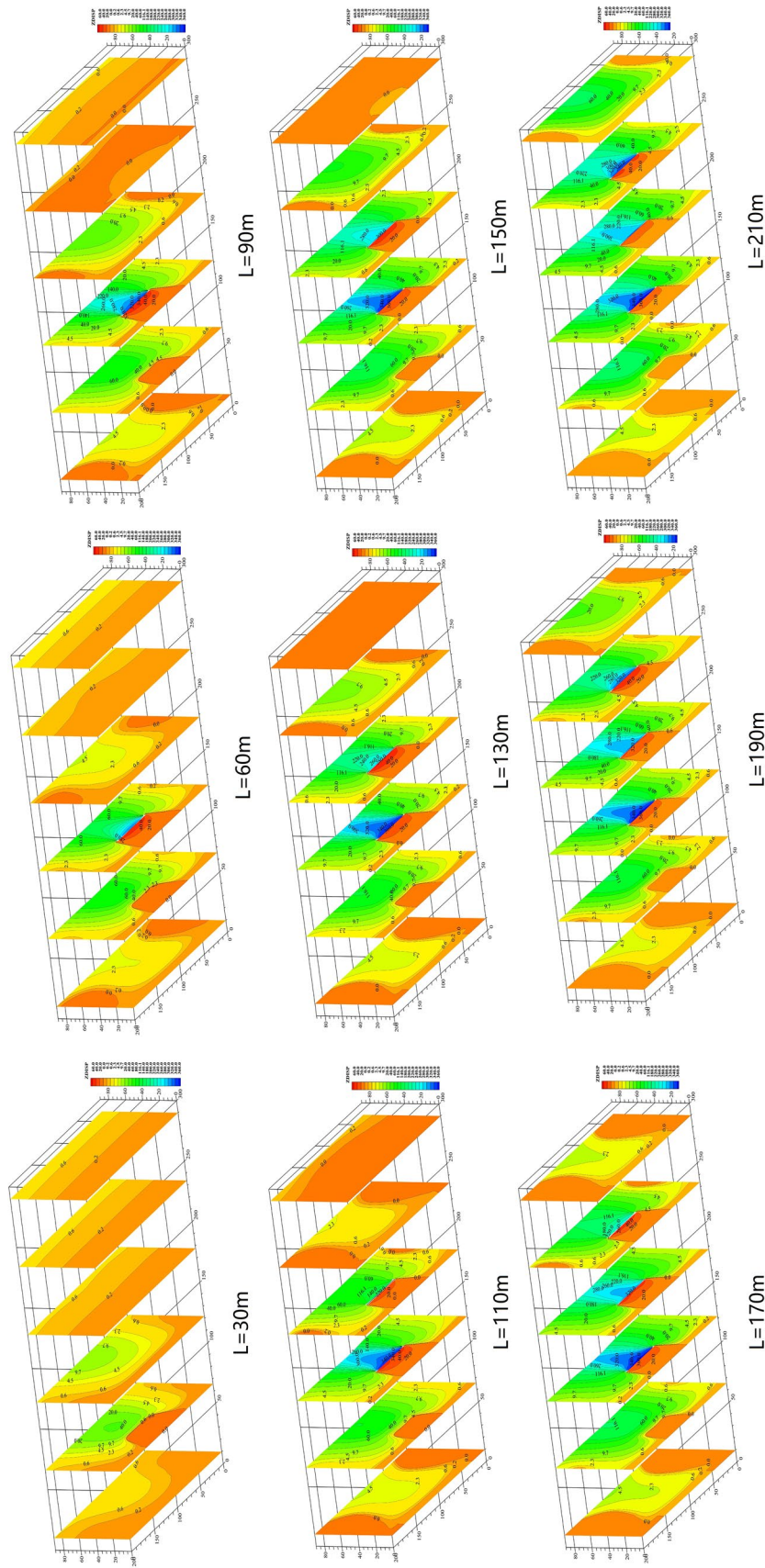


Fig. 9 Three-dimensional simulation map of vertical displacement field distribution of slope roof and floor under different propulsive degrees (L in the graph represents working face propelling distance and the unit in the graph is cm)

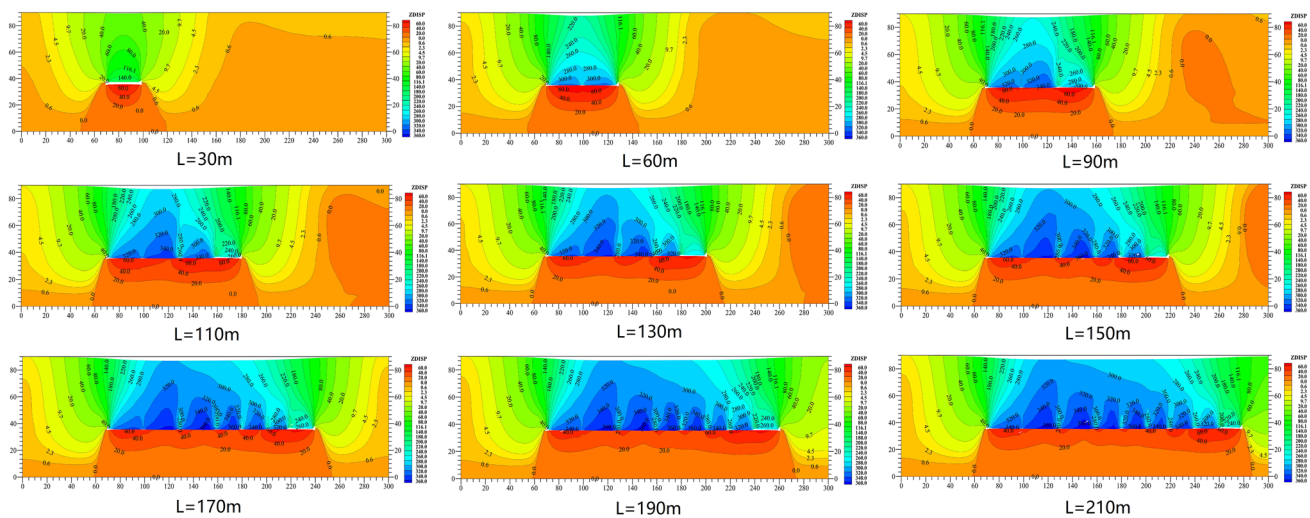


Fig. 10 Distribution law of vertical displacement field of stope roof and floor under different propulsive degrees ($Y = 100$ m) (L in the graph represents working face propelling distance and the unit in the graph is cm)

falling meteorites ($L = 20\text{--}110$ m). When the mining face is advanced to $L = 110\text{--}130$ m, the “wave form” in the goaf will no longer change significantly. The full mining distance is generally “1 initial pressure + 3~5 cycles to press”. When the working face is pushed over the full mining distance, the rock movement above the goaf will show a periodic “fall–fill–cut–top–compaction” process, which will start again and again until the end of the stoping.

(2) Dynamic variation law of strike support pressure.

As can be seen in Fig. 12, with the advancement of the working face, when the peak stress of the supporting pressure $k\gamma H$ (γ is the roof rock bulk density and H is the mining depth), the supporting pressure peak coefficient (k) is greater than the compressive strength of the coal wall at the mining face and the hole opening position, the plastic ring will occur in the coal wall, and the peak pressure will be transferred from the coal wall surface to the coal body, especially during the incomplete mining period. The performance of this process is very obvious. In the initial stage of the working face, the coal body is basically in an elastic state, and the supporting pressure distribution curve is a negative exponential function curve. The peak of the supporting pressure is located near the coal wall, for example, the supporting pressure peak coefficient $k = 1.436$ at $L = 30$ m. With the continuous advancement of the working face, the peak of the supporting pressure at the face is transferred to the deep part of the coal body ($k = 1.486$ at $L = 60$ m, $k = 1.480$ at $L = 110$ m), which is the dynamic support pressure evolution stage and the coal face of the mining face. Compared with the position support pressure peak, the support pressure at

the open cut position gradually increases as the mining width increases until the full production stage is reached.

For the supporting pressure of $Y = 160$ m, before the full mining stage, the supporting pressure on both sides of the mining face increases with the mining advancement, which is mainly affected by the structure of the overlying arched roof and the pressure of the roof. Coal body transfers around the goaf, such as $k = 1.03$ at $L = 30$ m, $k = 1.12$ at $L = 60$ m, and $k = 1.18$ at $L = 110$ m, until the goaf completely falls, cuts and compacts, reaching its maximum peak. The pressure will no longer increase. When the mining distance of coal seam exceeds full mining, the peak value of bearing pressure at $Y = 160$ m will no longer increase with the increase of mining distance, and the peak coefficient k of bearing pressure will remain in the range of 1.20–1.22.

For $Y = 190$ m, from the whole process of $L = 20\text{--}210$ m, the peak pressure coefficient k of the supporting pressure is in the range of 1.0–1.05, and the variation range is quite small, which can be neglected, indicating that the model is constructed reasonably and the data is accurate. The boundary is basically unaffected by mining.

Analysis of failure depth and development law of stope roof and floor

Figures 13 and 14 show the evolution law diagram of plastic zone of roof and floor in No. 5 coal seam 24,508 working face of Chenghe No. 2 Coal Mine under different excavation lengths.

From Figs. 13 and 14, it can be seen that when the working face is advancing 30 m, the direct roof of the working

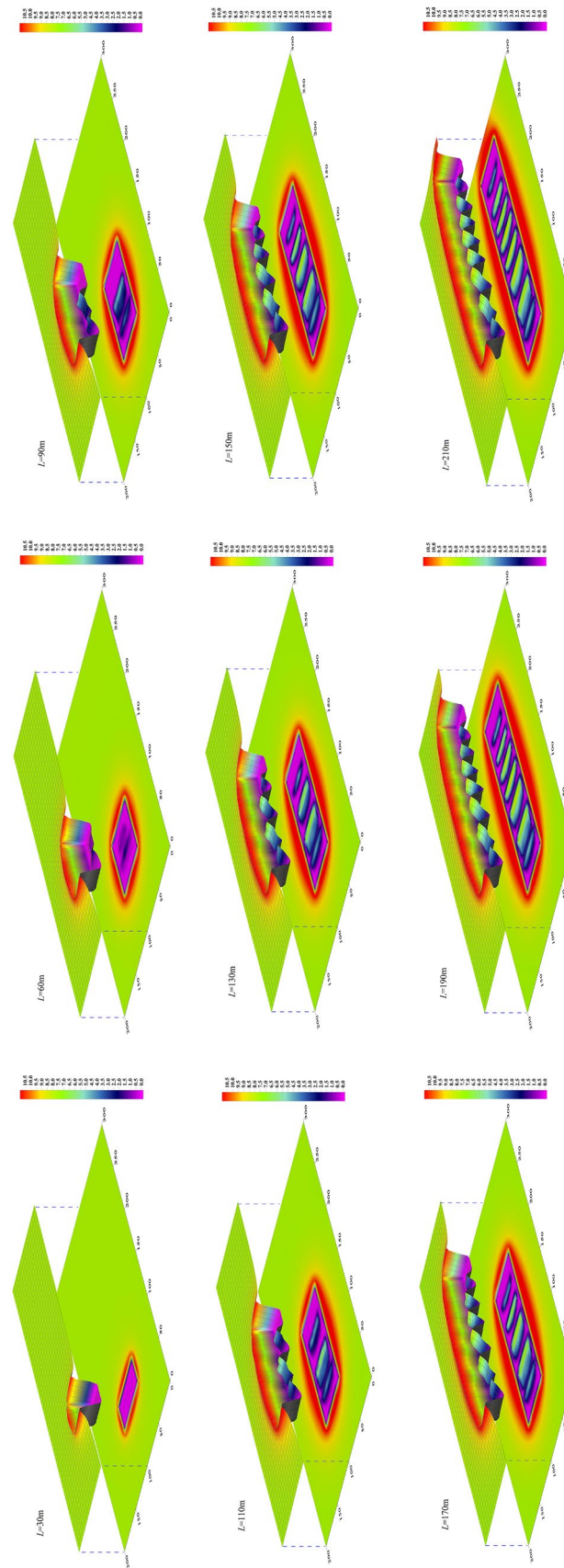


Fig. 11 Evolution law of support pressure of coal seam floor under different mining face propulsion distance

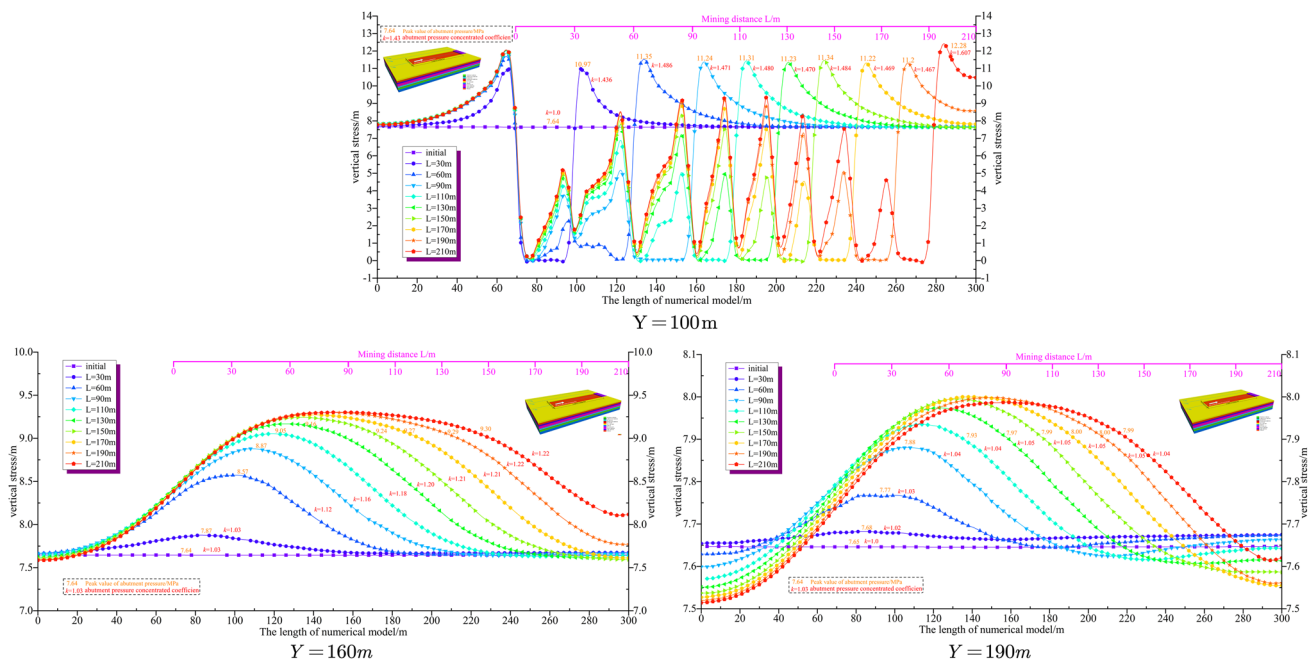


Fig. 12 Dynamic variation curve of strike support pressure at different cutting plane positions

face is mainly caused by tensile failure within the goaf area on the $X=66$ m section (the position of open-off cut is in the $X=70$ m) section, the height of water conduction fracture zone is only 20.9 m, the range of carving zone is direct roof, and the height is 3.15 m. The carving horizon is carbonaceous mudstone; however, the direct floor of goaf is damaged by tension deformation and failure (siltstone is the damage horizon). Shear failure occurred on both sides of the floor of the goaf, the failure depth of the floor was only 7.4 m, and the damage horizon was sandy mudstone. The overlying strata in goaf show a “saddle” shape.

When the working face is pushed to 60 m, on the section of $Y=122$ m, the direct roof of the face caving along with the mining, the height of the water-conducting fracture zone rises to 41.2 m (medium grain sandstone), and the height of carving zone rises to 10.6 m. The overall failure form shows an obvious “saddle shape”; the bottom plate forms an “M” shape, the siltstone direct floor still has tensile failure and extends to this sandy mudstone, and floor damage reaches 7.9 m (below the open-off cut). At this time, due to the thickness of the coal seam floor aquiclude is thick and the mining damage range of the floor is small, the Ordovician limestone confined water does not make the strata on the Ordovician limestone top interface produce failure height of the confined water guide zone.

When the working face is pushed to 90 m, the damage range of the overlying strata above the goaf is further expanded on the $Y=100$ m section, the height of the water-conducting fracture zone is maintained at 41.2 m (overlying rock), the height of the carving zone is still 10.6 m, and the

development height of the water-conducting fracture zone formed by the strata above the mining face is reduced by only 31.1 m, which is because the goaf far behind the mining face is basically filled and compacted by the carving gangue. However, the “M” shape of the floor of the goaf further enlarges to form a “wavy” shape, and the damage depth extends to the bottom of the sandy mudstone with a damage depth of 8.3 m.

When the working face is pushed to 110 m, the “saddle” shape is further expanded on the section of $Y=100$ m. The height of roof caving reaches 6.2 m (carbonaceous mudstone top), and the height of water-conducting fracture zone develops to 40.6 m. However, the maximum damage of the bottom plate in goaf occurs in the rock layer below the open-off cut and the coal face, develops inside the sandy mudstone, and the damage depth reaches 8.3 m. The height of the water-conducting fracture zone develops to about 35 m within the $X=178$ m section. The developmental horizon comprises medium grain sandstone, and the floor has a larger failure depth under the coal pillar and is located in the rock layer below the coal pillar.

When the working face is pushed to 130 m, the height of the roof water conduction fracture zone is maintained at 41.2 m. The depth of the mining failure of the bottom plate is not extended to the depth, but is maintained at 8.3 m. In the section of $X=178$ m, the failure form of the direct roof in goaf has not changed obviously, the longitudinal damage range extends upward, and the height of development is smaller than that of the strike section. The main failure of the goaf floor is shear failure, and the damage depth is 7.8 m.

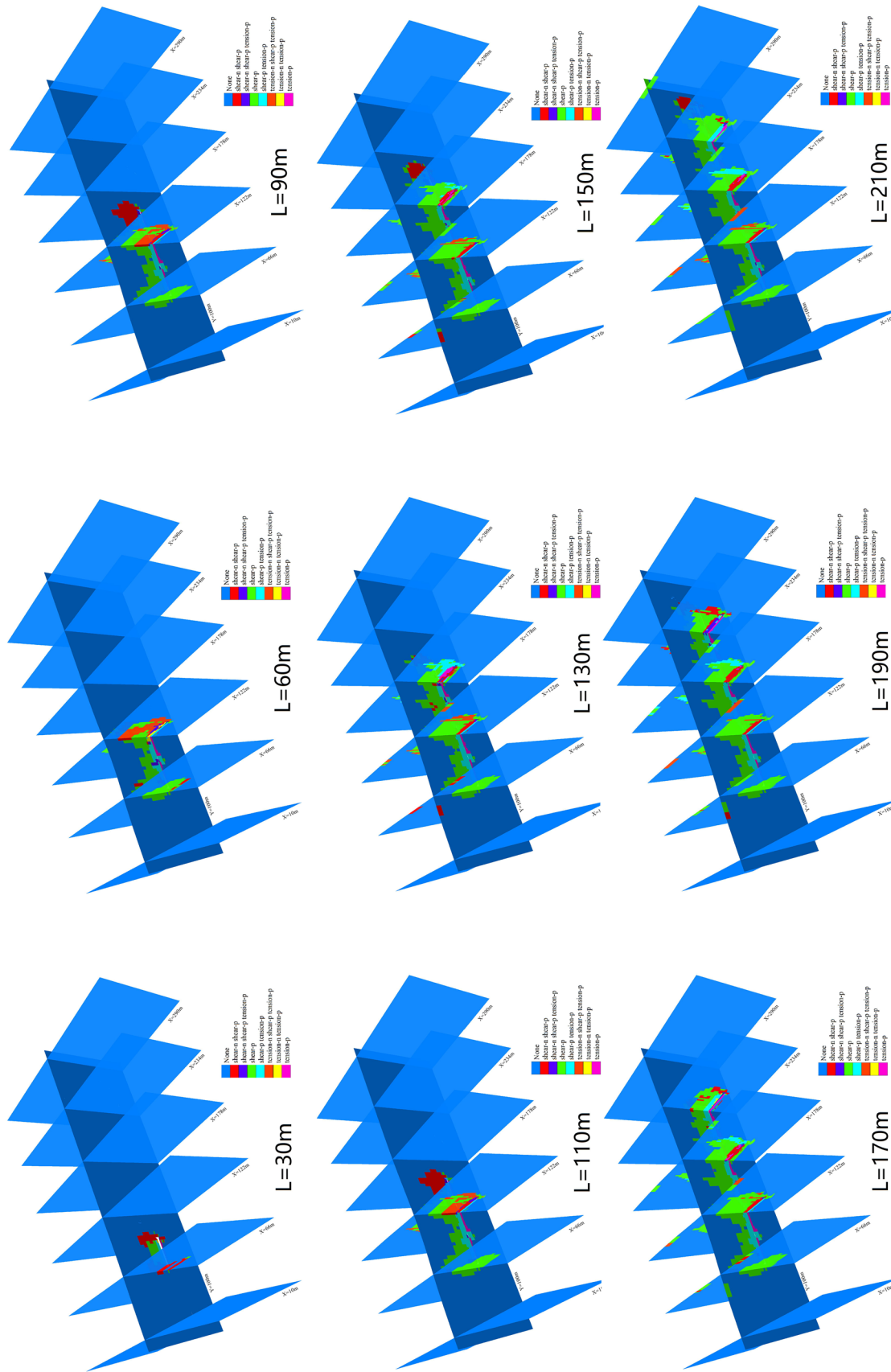


Fig. 13 Three-dimensional simulation of plastic development law of slope roof and floor under different propulsive degrees (L in the graph represents working face propelling distance)

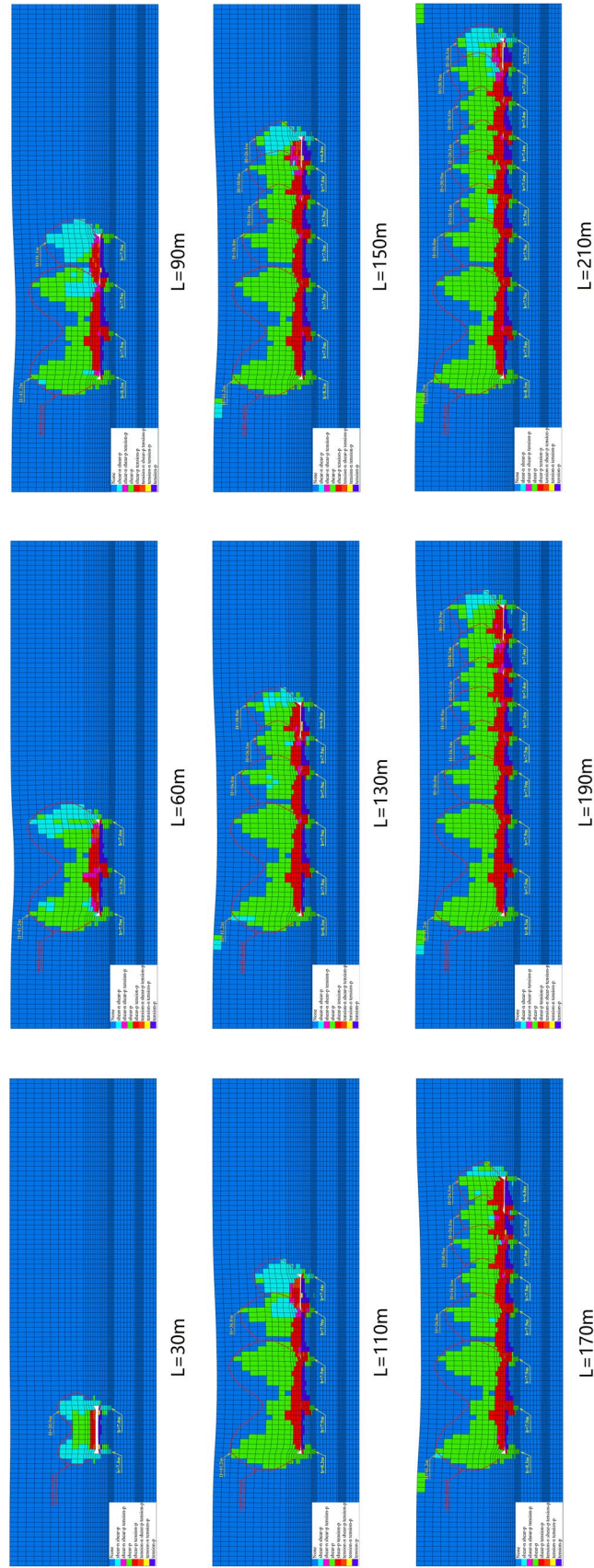


Fig. 14 Plastic development law of slope roof and floor under different propulsive degrees (L in the graph represents working face propelling distance)

When the working face continues to move forward to 130–210 m, the height of the overlying rock layer water-conducting fracture zone of the goaf near one side of the open-off cut is not more than 41.2 m on the $Y=100$ m section. This is due to the smaller range of pressure arch formed subsequently, and the failure forms begin again and again. The height of the water-conducting fracture zone at the top of the goaf increases with the development of mining, which is close to the side of the coal face in the pressure range of one to two cycles. However, the development height is smaller than that near the open-off cut side, which is mainly due to the small pressure arch height formed by the overlying strata in the goaf. The failure depth of the bottom plate is lower than that of the goaf compaction, which is kept in the range of 6.8–7.9 m, but less than 8.3 m.

Floor mining failure depth simulation results analysis

The whole development process of floor mining failure depth linearly increases along with the development of mining face, and then tends to becoming steady. When the propulsion distance of the working face is less than 90 m (1.5 times cut width), the depth of floor mining failure increases linearly with the advance of mining face, but when the working face is over 90 m, the depth of floor mining failure no longer changes with the mining face and is basically stable at 8.3 m. Since then, the working face continued to advance, and the failure depth of the bottom plate was basically maintained at that depth.

Results analysis of field test

Borehole test was conducted from 1.5 to 13.0 m for effective observation depth (vertical depth). This 24,508 working face coal seam floor failure depth observation method used multiple point displacement meter (national invention patent: ZL201310614482.5; utility model patent: ZL201621021735.3) field test, through the pre-arrangement of drilling and monitoring equipment at a distance of 50 m from the coal mining surface. The actual observation begins at 28 m distance from the coal face, and the monitoring equipment can be placed at the borehole before coal seam mining (as shown in Fig. 5). Through the monitoring equipment, the high precision displacement meter (precision: 0.01 mm) is used to read the data directly. When the working face is near the measuring point, the steel pipe can be buried above the hole, and the steel pipe can be laid along the driving direction of the air return way to 25 m away from the measuring point for continuous observation. Therefore, when the measuring point enters the goaf, the observation can be continued through the buried pipe until the observation point is stabilized.

The relative displacement between the measuring points and the porthole of 24,508 working face coal seam floor is shown in Fig. 15; the relative displacement of the adjacent measuring points at the failure depth of coal seam floor in 24,508 working face is shown in Fig. 16. The three-dimensional relation curve of the relative displacement of the floor rock during the stoping period of 24,508 working face is shown in Fig. 17.

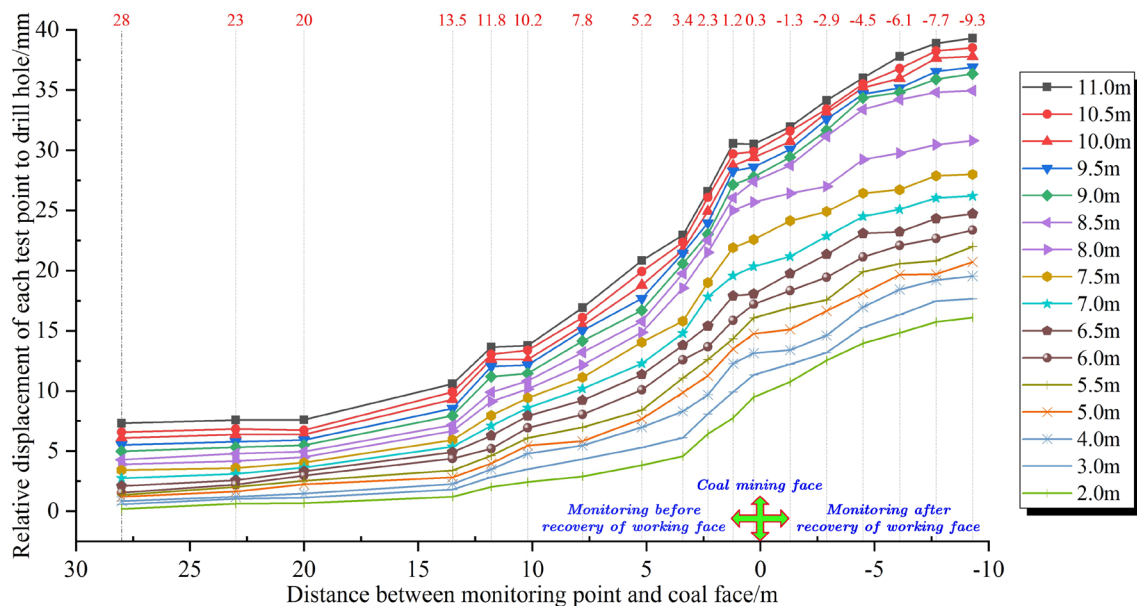


Fig. 15 The relationship diagram between the relative displacement between the measuring points and the stoping surface propulsive degree

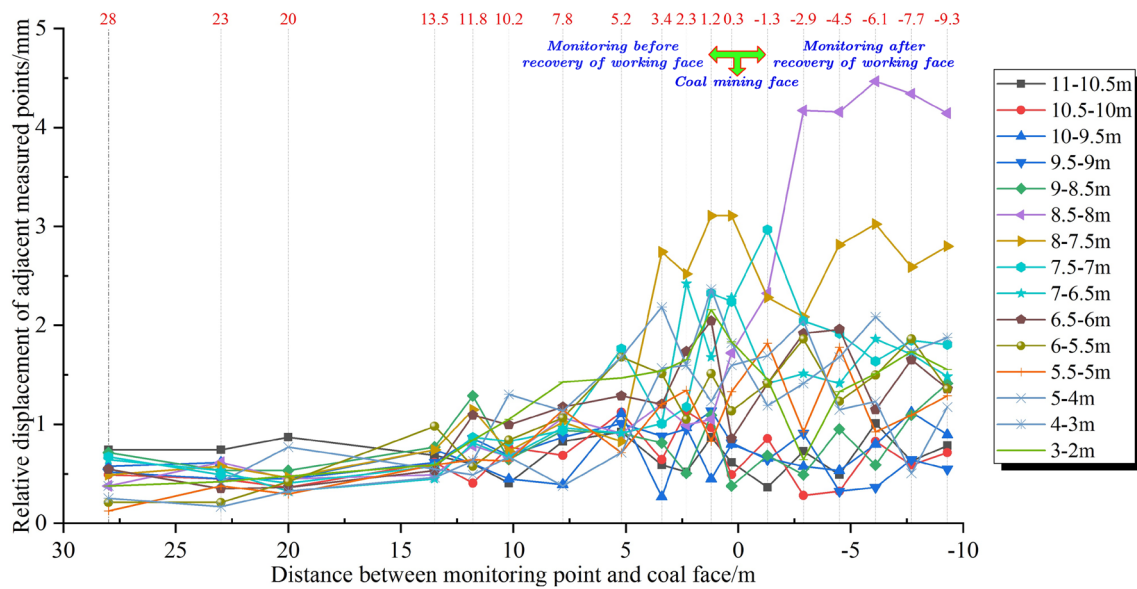
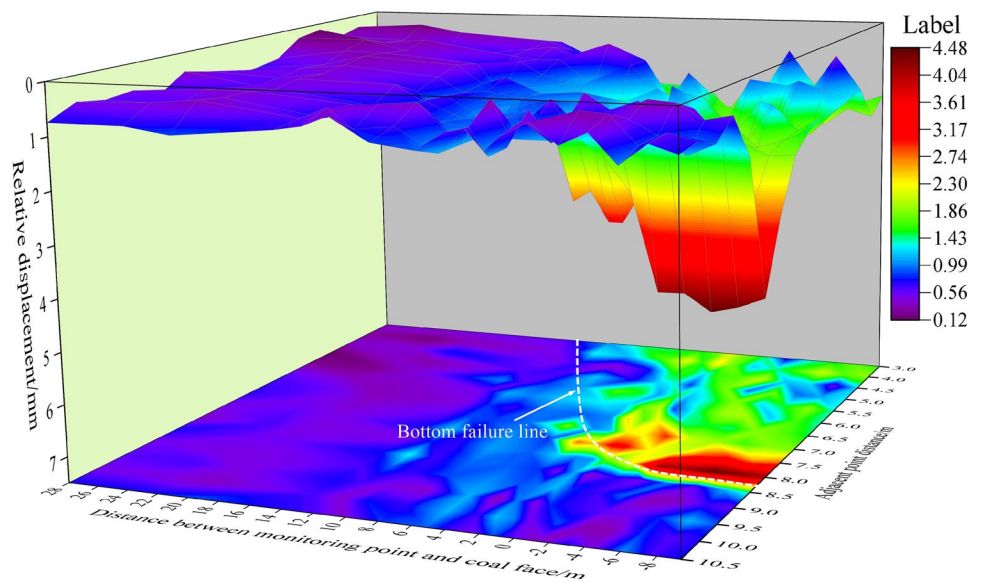


Fig. 16 The relationship diagram between relative displacement of adjacent measuring points and stoping surface propulsive degree

Fig. 17 The relationship curve diagram of relative displacement of floor strata during backstopping period of 24,508 working face



From Figs. 15, 16 and 17, it can be seen that when the 24,508 coal mining surface is pushed from the coal mining surface to the horizontal distance from the drilling pit test point to 28–13.5 m before mining, because the floor is in the original rock stress state, there is no obvious relative displacement of the measuring points in the bottom rock layer. In Fig. 15, the change is slightly increased, mainly due to the roadway floor heave; when the 24,508 coal mining surface is pushed to the horizontal distance of 10.2 m from the test point of drilling pit, the relative displacement of the adjacent measuring points begins to change slightly. It can also be seen from Fig. 17 that the relative displacement range of this segment is in 0.12–0.56 mm (purple part); from

the point of 10.2–1.2 m before mining, the relative displacement value changes obviously, which is mainly affected by the coal seam mining. When the working face of the mining face gradually advances to the drilling hole measuring point, the stress of the old main roof is transferred to the coal seam. The change of the supporting pressure will affect the change of the maximum and minimum principal stress of the coal seam floor, thus causing the change of the displacement field of the floor. From 1.2 to –6.1 m in the mining, the relative displacement value increases with the propulsive degree, and reaches the maximum near the measuring point 6.1 m (the measuring point has entered the goaf) in 24,508 mining face (8.0–8.5 m curve in Fig. 16). Because the roof of overlying

strata is just in the cantilever beam, the maximum principal stress decreases, the horizontal stress perpendicular to the direction of the working face increases, and the crack in the horizontal direction begins to squeeze. The horizontal crack began to decrease gradually, the additional stress of the goaf floor was reduced by the carving gangue, the displacement of the floor increased, and the floor of the goaf increased. The maximum value of plastic slip occurred in rock formation in this interval, the maximum relative displacement of each measuring point can reach 4.34 mm, the maximum relative displacement of each measuring point can reach 1.825 mm between the interval measurements, and the distance between each measuring point is drilling hole. Within the distance of -6.1 to -9.3 m after mining, the depth of disturbance failure of the bottom plate does not continue to develop into the deep strata, but terminates at the depth of 8.0–8.5 m (vertical depth). When the depth of the observation point is greater than 8.5 m, there is no significant fluctuation in the data waveform. In Fig. 17, it can be seen that most of the areas greater than 8.5 m are purple areas, and the relative displacement range is 0.9–0.12 mm. It also shows that the rock mass at the depth of 8.5–11.0 m is not affected by coal seam mining and is always in the range of elastic stress change. At the same time, as the coal face continues to advance, the old main roof is compacted again after mining, the maximum principal stress increases gradually, the supporting pressure after mining tends to be stable, and the goaf is basically compacted by the carving gangue. The internal stress of the floor rock mass tends to be stable basically. At this time, the internal stress of the floor rock mass should be subjected to elastic stress, and the displacement of the bottom plate of the measuring point will no longer change with the continuous advance of the coal mining surface. This can be confirmed by numerical simulation.

Comparison between numerical simulation and field measurement results

The failure depth of floor rock layer of No. 5 coal seam was carried out during the backstopping period of 24,508 working face of No. 5 Coal seam in Chenghe No. 2 Coal Mine. The method of “displacement monitoring of floor rock layer” was adopted in the field, and a multiple point displacement meter was set up every half meter along the borehole. To determine the failure depth of the coal seam floor, the change of rock displacement of floor drilling is determined, and the research results are as above.

According to the relationship curve diagram of relative displacement of floor rock layer during the backstopping period in 24,508 working face of Chenghe No. 2 Coal Mine, it can be seen from Figs. 15, 16 and 17 that the development degree of floor failure is obvious in boreholes. Along

with the continuous advance of the mining face, the cracks began to develop gradually at the hole depth of 1.5–8.5 m. When the monitoring point goes over the mining surface and enters the goaf (1.2 ~ -6.1 m interval), the plastic slip of the bottom plate in this interval will reach the maximum value. Figure 17 shows that at the bottom failure line, this curve terminates in the range of 8.0–8.5 m. The degree of fracture development is related to the lithology of the area, and the original fissure is not developed under the depth of 8.5 m. No obvious fissure occurs due to the influence of mining.

Based on the above analysis, it can be seen from the field monitoring data that the maximum failure depth of the floor measured directly below the coal body is 8.0–8.5 m. Combined with the results of numerical simulation, the maximum failure depth of the floor of No. 5 coal seam in 24,508 working face is 8.3 m.

Most of the statistical data of the statistical formulas in China's Coal Mine Safety regulations and regulations on Water Prevention and Control of Coal Mines concentrate on the values of the damage depth of the floor collected under the conditions of shallow buried depth and lower mining height. According to the previous measured results, when the buried depth is basically not affected by the mining height in the shallow part, the analysis shows that the stress state of the rock mass changes when the buried depth is large, and the coal seam mining begins to transition to the plastic deformation stage. The change of supporting pressure around the goaf will greatly affect the failure and deformation of the floor rock mass. Therefore, under the condition of 400 m mining depth, the influence of mining height on the floor failure is greater than that in the shallow part, and the depth of the bottom plate failure will change greatly. The prediction of the depth of the floor disturbance damage can be carried out only by relying on the empirical formula in the code and the rules. It is very likely that the actual failure depth value and the predicted depth value will be in great error, which is disadvantageous to the prevention and treatment of mine floor water hazard. Therefore, the result of disturbance and failure of coal seam floor in Chenghe Coal Mine obtained by numerical simulation and field measurement method is closer to the true value, which will bring huge economic benefits to the smooth development of the prevention and control of water in the later stage of mine.

Conclusion

To solve the problem of safe mining of coal seam No. 5 in Chenghe No. 2 Coal Mine, this paper has carried out numerical simulation analysis of floor failure mechanism of coal seam No. 5 in Chenghe Coal Mine and research on field measurement technology. Based on the measured data and simulation results, the deformation and failure depth of floor

strata are analyzed and studied, which has great significance to ensure the safe production of No. 5 coal seam in Chenghe mining area. The following conclusions are drawn:

1. In this paper, numerical simulation of failure mechanism of stope floor is carried out in No. 5 coal seam of Chenghe No. 2 Coal Mine. The disturbance and failure situation and its law of floor in Chenghe Coal Mine have not been revealed at home and abroad so far. The FLAC^{3D} numerical simulation software is used to simulate and analyze the development height of the overlying strata water-conducting fracture zone and the depth of the floor disturbance before and after coal seam mining. With the continuous advancement of the working face according to a certain step distance, under the action of stress field and seepage field, the distribution law of plastic zone, stress distribution and displacement field of mining surrounding rock in No. 5 coal seam are simulated, respectively. It is concluded that the fracture depth of floor in No. 24,508 working face of Chenghe No. 2 Coal Mine is 8.3 m.
2. With coal seam mining, the stress of coal rock mass is redistributed around the goaf. When the stress value near the coal wall reaches the strength limit of the coal seam, as the coal body breaks, its bearing capacity decreases, and the pressure peak near the coal wall will go deep into the coal body. When the peak bearing pressure is transferred to the deep part of the coal body, the elastic pressure zone and the plastic zone will be generated in the support pressure distribution zone. The high peak of the stress is located at the junction of the elastic zone and the plastic zone. The coal seam is connected with the bottom plate, and the plastic zone of the coal seam will bring the plastic slip of the floor, resulting in plastic failure of the floor. When the mining face is advanced to a certain distance, as the goaf is gradually filled with falling meteorites, the upper part of the rock is laminated with solid goaf, and the bottom plate supporting pressure in the goaf is gradually. It recovers and tends to stabilize until it is fully compacted. At this time, the distance of the working face advancing is usually 1 first weighting plus 3 to 5 periodic weighting.
3. According to the principle that the bottom rock layer changes with the stress field inside the rock mass, the characteristics of the relative displacement change are observed repeatedly before and after mining, and the results of the relative displacement change are analyzed. The mining failure depth of floor before and after coal seam mining is obtained. The field test starts at 28 m distance from the working face. The author's patent technology is used to carry out the field measurement. The observation technology of the observation point entering the goaf is carried out for the first time by using the

method of embedded pipe. The accuracy and rationality of this method are verified by the results of numerical simulation and more than a 1000 groups of data are obtained. Through the actual measurement of the floor of the drilling hole in No. 5 coal seam of Chenghe No. 2 Coal Mine during the backstopping period, it can be seen that the fluctuation of the relative displacement of the measured points in the vertical depth of 8.0–8.5 m test section is the most significant, and the relative displacement reaches the maximum value when the working face is mined to the measuring point of 1.2 to – 6.1 m, indicating that the floor rock fracture develops to this depth. The bottom plate of the test section of 8.5–11.0 m is still in the area of elastic change, and the relative displacement is smaller, which indicates that the fracture of the bottom rock layer has not developed at this point.

4. According to the data of statistical formula in “Coal Mine Safety regulations” and “Coal Mine Water Prevention regulations”, most of the data sources are based on the regression formula obtained on the basis of the data collected under the condition of shallow buried depth and less mining height. During the application of grouting on the floor of No. 5 coal seam in Chenghe No. 2 Coal Mine, it is very likely that the actual failure depth value and the predicted depth value will be in great error. Therefore, the measured results and numerical simulation results obtained by the multiple point displacement method show that the maximum failure depth of mining movement in 24,508 working face is 8.3 m, thus the mining failure depth of floor rock mass during coal seam mining is quantitatively analyzed. The conclusions obtained in this paper have relatively high application value in predicting the depth of floor failure in Chenghe mining area, which can basically meet the practical needs of engineering and bring huge economic and social benefits to mine water prevention and safety production.

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References

- Chi MB, Zhang DS, Liu HL, Wang HZ, Zhou YZ, Zhang S, Yu W, Liang SS, Zhao Q (2019) Simulation analysis of water resource damage feature and development degree of mining-induced fracture at ecologically fragile mining area. *Environ Earth Sci* 78(3):88
- Dai GL, Xue XY, Xu K, Dong L, Niu C (2018) A GIS-based method of risk assessment on no. 11 coal-floor water inrush from Ordovician limestone in Hancheng mining area, China. *Arab J Geosci* 11(22):714
- Gu SC, Li A (2011) Application of mine electric method to probe mine water-conducting or water-bearing structures in potential under coal mining face floor. *MACE* 2011:7213–7219
- Guo WJ, Zhao JH, Yin LM, Kong DZ (2017) Simulating research on pressure distribution of floor pore water based on fluid-solid coupling. *Arab J Geosci* 10(1):5
- Kong DZ, Jiang W, Chen Y, Song ZY, Ma ZQ (2017) Study of roof stability of the end of working face in upward longwall top coal. *Arab J Geosci* 10(8):185
- Li A (2012) Water inrush mechanism of seepage and stress coupling failure of floor under mining under pressure and its engineering application. Doctoral dissertation, Xi'an University of Science and Technology
- Li A (2014) Experimental research of seepage characteristics caused by coal floor rock full of stress and strain process, operated by No. 5 Taiyuan group. In: *The 3rd ISRM/International Young Scholars' Symposium on Rock Mechanics*, pp 7213–7219
- Li A (2015) Water inrush mechanism and application of mining floor failure in confined water body of Weibei coalfield. China University of Mining and Technology Press, Xuzhou
- Li A (2016) Monitoring and measuring device, installation and measuring method of multi-point separation of surrounding rock mass in Roadway, China, ZL201310614482.5[P].2016-06-15
- Li A, Li KF (2016) Floor water inrush risk evaluation for mining above confined aquifer in No. 5 coal seam of Taiyuan group at Dongjiahe coal mine. *Electron J Geotech Eng* 21(5):1809–1822
- Li A, Gu SC, Chen FF (2013) Theoretical analysis and numerical simulation of destroyed depth of coal seam floor during bearing mining: with seam No. 5 in Dongjiahe. *Mine, Chenghe Mining Area Shaanxi as Example. Coal Geol Explor* 41(4):56–60
- Li A, Liu Y, Mou L (2009) Impact of the panel width and overburden depth on floor damage depth in no. 5 coal seam of Taiyuan Group in Chenghe Mining Area. *Electron J Geotech Eng* 20(6):1603–1617
- Li A, Li RN, Wang P, Liu TT, Yu J, Li XY (2017a) Borehole anchorage structure used to monitor cracks in surrounding rock of floor: China, ZL201621021735.3[P].2017-05-03
- Li H, Bai HB, Wu JJ, Wang CS, Ma ZG, Du YB, Ma K China Arab J Geosci 10(21):468
- Li A, Liu Y, Mou L (2018a) Numerical analysis and case study on the mitigation of mining damage to the floor of no. 5 coal seam of Taiyuan Group by grouting. *J S Afr Min Metall* 118:5
- Li A, Ma Q, Kang L, Li L, Cai L, Wang W (2018b) Evaluation on floor water inrush danger of Weibei during mining over pressurized water and prevention countermeasures to the water disaster. *J Mines Metals Fuels* 66(4):231–244
- Li HJ, Chen QT, Shu ZY, Li L, Zhang YC (2018c) On prevention and mechanism of bed separation water inrush for thick coal seams: a case study in China. *Environ Earth Sci* 77(22):759
- Liang YP, Li B, Zou QL (2019) Movement type of the first subordinate key stratum and its influence on strata behavior in the fully mechanized face with large mining height. *Arab J Geosci* 12(2):31
- Liu SL, Liu WT, Yin DW (2017a) Numerical simulation of the lagging water inrush process from insidious fault in coal seam floor. *Geotech Geol Eng* 35(3):1013–1021
- Liu YJ, Xue JH, Yuan L, Yu GF, Tian ZC, Chen BL (2017b) Numerical test and mechanism analysis of water inrush on soft rock floor. *J China Coal Soc* 42(12):3255–3261
- Liu WT, Mu DR, Xie XX, Li Y, Wang DH (2018a) Sensitivity analysis of the main factors controlling floor failure depth and a risk evaluation of floor water inrush for an inclined coal seam. *Mine Water Environ* 37(4):636–648
- Liu WT, Li Q, Zhao JY, Fu B (2018b) Assessment of water inrush risk using the principal component logistic regression model in the Pandao coal mine. *China Arab J Geosci* 11(16):463
- Lu YL, Wang LG (2015) Numerical simulation of mining-induced fracture evolution and water flow in coal seam floor above a confined aquifer. *Comput Geotech* 67:157–171
- Ma Q, Tan YL, Zhao ZH, Xu Q, Wang J, Ding K (2018) Roadside support schemes numerical simulation and field monitoring of gob-side entry retaining in soft floor and hard roof. *Arab J Geosci* 11(22):563
- Meng XX, Liu WT, Mu DR (2018) Influence analysis of mining's effect on failure characteristics of a coal seam floor with faults: a numerical simulation case study in the Zhaolou coal mine. *Mine Water Environ* 37(4):754–762
- Su PL, Gu SC, Li A (2014) Analysis on Site measurement and simulation of floor failure depth under condition of deep mining depth in Dongjiahe mine. *Coal Eng* 46(04):93–95
- Sun J, Wang LG, Hu Y (2018) Mechanical criteria and sensitivity analysis of water inrush through a mining fault above confined aquifers. *Arab J Geosci* 12(2):4
- Wu Q, Wang M, Wu X (2004) Investigations of groundwater bursting into coal mine seam floors from fault zones. *Int J Rock Mech Min Sci* 41(4):557–571
- Xiao HT, Wen XL, Zhang WQ, Li BY (2001) In situ measurement of floor strata displacements in slice mining. *Chin J Geotech Eng* 20(5):20–338. <https://doi.org/10.1038/nrc1074>
- Yin HY, Wei JC, Leticariu L, Guo JB, Xie DL, Li ZL, Zhao P (2016) Numerical simulation of water flow from the coal seam floor in a deep longwall mine in China. *Comput Geotech* 32(2):243–252
- Yin HY, Sang SZ, Xie DL, Zhao H, Li SJ, Li HS, Zhuang XH (2019) A numerical simulation technique to study fault activation characteristics during mining between fault bundles. *Environ Earth Sci* 78(5):148
- Zhai XR, Zhang HM, Dou ZS, Shen JW, Shen SH, Zhou SQ (2016) Study on fluid-solid coupling mechanism for water resistance effect of coal floor based on different combination of rock strata. *J Saf Sci Technol* 20:20
- Zhang CL, Liu L, Wang C (2016a) Advanced rock mechanics and engineering application. Central South University Press, Changsha
- Zhang NB, Liu CY, Yang PJ (2016b) Flow of top coal and roof rock and loss of top coal in fully mechanized top coal caving mining of extra thick coal seams. *Arab J Geosci* 9(6):465
- Zhang S, Guo W, Li Y (2017) Experimental simulation of water-inrush disaster from the floor of mine and its mechanism investigation. *Arab J Geosci* 10(22):503
- Zhu WB, Yu SC, Xuan DY, Shan ZJ, Xu JL (2018) Experimental study on excavating strip coal pillars using caving zone backfill technology. *Arab J Geosci* 11(18):554

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