

Characteristics Analysis of Roof Overburden Fracture in Thick Coal Seam in Deep Mining and Engineering Application of Super High Water Material in Backfill Mining

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Abstract With the development of deep mining, the mining pressure on the working face is increasing, the failure height of thick seam roof is increasing, and the failure characteristics of roof are becoming more complex. The cracks in the overlying strata of the roof are greatly increased and activated by mining influence, which increases the impervious threat of the roof. In order to solve this problem, the failure stress model of thick coal seam roof was established; the 1308 working face of Yancheng Coal Mine was taken as the engineering background, and the FLAC3D numerical simulation software was used to simulate the formation failure process of 1308 working face with the threat of water permeability; the drilling section water injection test method was used to measure 1308 working face; High water material is used as raw material to fill 1308 working face. The results show that: (1) the failure height of overlying strata is calculated more accurately by mechanical model, and the failure characteristics are analyzed; (2) the failure height of overlying strata calculated by numerical simulation is smaller than that calculated by theory; (3) the problem of serious roof caving in thick coal seam can be effectively alleviated by filling with super-high water material.

Keywords Deep mining · Thick coal seam · Numerical simulation · Super high water material · Grouting filling

1 Introduction

With the increase of the depth of coal seam mining, the height of roof failure increases continuously, and the number of cracks in the roof rock also increases greatly (Jiang et al. 2016; He et al. 2016; Zhu et al. 2016). In the process of deep mining thick coal seam, the roof is often severely damaged, the cracks are developed and enlarged, and water inrush accidents are easy to occur (Yu et al. 2007; Zhang et al. 2017; Li et al. 2018). At present, numerical simulation, similar simulation experiment, drilling flushing fluid consumption, empirical formula calculation method and field measurement method are generally used to determine the height of water conduction fracture zone in roof overburden mining at home and abroad (Chen et al. 2016; Liu et al. 2017). Research on overburden failure has made great achievements both at home and abroad. Former Soviet scholar Kuznetsov put forward the articulated rock block hypothesis in the 1950s in combination with the sequence of roof strata collapse. The hypothesis zoned the overlying strata in the goaf and gave the possible “structure” and discussed the mechanical relationship within the

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strata. A Belgian scholar A. Labes put forward the hypothesis of precrack in the 20th century. Belgian scholar A. 1950s, proposed the preformed fissure hypothesis. In the middle and later years of the 1970s, academician Qian Minggao, a scholar in China, summarized the experimental results of the migration law of overlying strata, developed the articulated rock block hypothesis and the pre-formed crack hypothesis, put forward the masonry beam hypothesis, and established the masonry beam structural model of overlying strata in stope according to the experimental results and the observation results of Engineering practice. At the beginning of this century, academician Qian Minggao further developed the theory of mine pressure based on the mechanics model of masonry beam in stope and the law of stratum movement, and put forward the theory of key stratum in stratum control (Qian 1996).

Professor Yang Baogui and others used similar material simulation method to study the law of ground pressure in cemented filling mining face; obtained the maximum value and location of vertical stress on the backfill; analyzed the distribution of supporting pressure in front and back of the working face; analyzed the maximum displacement and the occurrence of the roof above the backfill in the goaf. It is concluded that cemented filling mining can effectively control the movement of overlying strata (Baogui et al. 2015; Yang et al. 2013). Professor Wang Jiachen and others combined physical simulation with numerical calculation and field measurement to simulate the process of working face mining and waste filling. The movement and deformation forms of the direct roof and the basic roof are obtained, and the relationship model between the support and the surrounding rock is established (Wang and Wang 2015). Professor Zhang Jixiong and others applied the theory of elastic foundation beam to the analysis of bending deformation of key stratum, obtained the deformation characteristics and maximum deflection of key stratum, and analyzed the influence of lithology of lower stratum and filling material on elastic foundation coefficient and the quantitative relationship between them (Zhang et al. 2011a, b). Professor Liu Weitao combines the measured and numerical simulation methods of roof overburden failure with the multi-stage plugging observation system, which provides a good practice for the detection of roof overburden failure (Liu et al. 2017). Based on the key stratum theory, Xu Jialin put

forward the strip filling mining method with paste cementitious material filling. By constructing the filling strip, the mechanical structure system of “filling strip—roof stratum—main key stratum” was analyzed. The technical principle and applicability of the method were studied, and the corresponding engineering practice was carried out (Xu et al. 2005).

The above scholars have achieved great success in their research, but they have not involved in the analysis of roof fracture characteristics of thick coal seams, nor have they put forward effective solutions to this problem. Combining with the geological conditions of 1308 working face in Yuncheng Coal Mine, this paper establishes a mechanical model of roof failure in thick seam to analyze the height and characteristics of overburden failure. The characteristics of roof failure are analyzed by FLAC3D numerical simulation software. The height of overburden failure is measured by drilling and sublevel water injection test method, and the method of filling mining is adopted. Super high water material is used as raw material for filling mining practice.

2 Mechanical Analysis of Roof Overburden Failure in Thick Coal Seam

For thick seam mining, due to the large mining height of roof collapse and backwardness, the upper part of caving body and the lower part of fracture zone are often left with larger free space, which also leads to the reduction of natural filling rate of goaf (Xie et al. 2016; Zhang et al. 2016). With the passage of time, the fracture zone will continue to develop under ground pressure, then collapse, and then form new fracture zone and curved subsidence zone. This phenomenon is called the caving cycle, which stops when the fractured zone contacts the key stratum.

2.1 Failure Analysis of Overlying Strata in Short Working Face

In order to study the failure height of overlying rock in short working face of thick coal seam, according to the theory of rock pressure, combining the roof caving law and roof support pressure distribution law of mechanized mining, the roof stress distribution diagram of short working face in thick coal seam is established (Fig. 1). According to the theory of material

mechanics, the short working face of thick coal seam is simplified as simply supported beam structure (Fig. 2). The mechanics model for calculating the failure height of roof overburden in thick coal seam is established. The support force in Fig. 1 is simplified as F_1 and F_2 , and the pressure on roof is simplified as q_1 . According to the theory of semi-infinite body, the density of overlying strata is set as ρ , the original height of overlying strata is set as H_1 , and the area of overlying strata is set as A_1 . After the coal mining, the overburden strata and the coal and rock support can be balanced when the caving cycle ends. At this point, the uniform load is q_1 , the supporting force is F_1 and F_2 , and the failure height of overlying rock is h_1 according to the mechanical equilibrium condition.

$$\rho H_1 A_1 g - (F_1 + F_2) = \rho h_1 A_1 g \tag{1}$$

$$\rho H_1 A_1 g - q_1 (L_1 + L_2 + L_3) = \rho h_1 A_1 g \tag{2}$$

$$h_1 = H_1 - \frac{q(L_1 + L_2 + L_3)}{\rho A_1 g} \tag{3}$$

2.2 Failure Analysis of Overlying Strata in Long Working Face

According to the above theory, the roof stress distribution map of long coal face in thick coal seam is established (Fig. 3). After mining, the span of goaf is large, and the effect of mine pressure on roof is actually disconnected in the middle of goaf. With this boundary, the left and right forces are symmetrical to

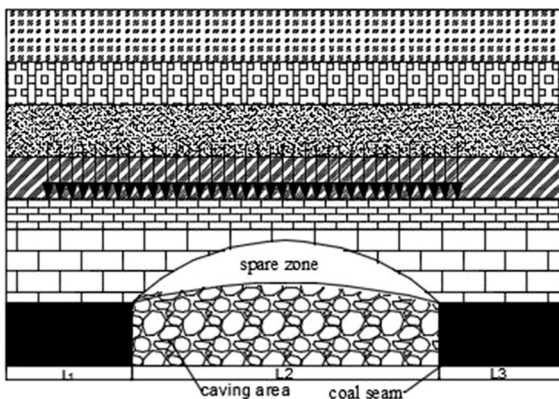


Fig. 1 Stress distribution diagram of short coal face in thick coal seam

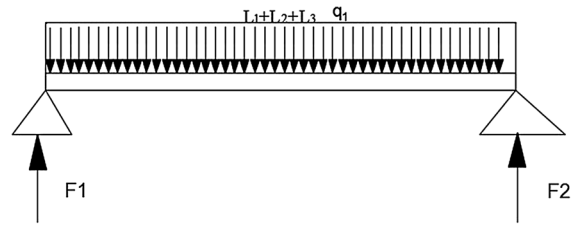


Fig. 2 Simplified mechanics model for short working face in thick coal seam

each other, so it can be simplified as the left and right outrigger beams (Fig. 4).

According to the theory of semi-infinite body, the density of overlying strata is set as ρ , the original height of overlying strata is set as H_2 , and the area of overlying strata is set as A_2 . After the coal mining, the overburden strata and the coal and rock support can be balanced when the caving cycle ends.

At this point, the uniform load is q_2 , the supporting force is F_3 and F_4 , and the failure height of overlying rock is h_2 according to the mechanical equilibrium condition.

$$\frac{1}{2} \rho H_2 A_2 g - (F_3 + F_4) = \frac{1}{2} \rho h_2 A_2 g \tag{4}$$

$$\frac{1}{2} \rho H_2 A_2 g - q_2 \left(L_4 + \frac{1}{2} L_5 \right) = \frac{1}{2} \rho h_2 A_2 g \tag{5}$$

$$h_{21} = H_2 - \frac{q_2 (2L_4 + L_5)}{\rho A_2 g} \tag{6}$$

$$\frac{1}{2} \rho H_2 A_2 g - (F_5 + F_6) = \frac{1}{2} \rho h_2 A_2 g \tag{7}$$

$$\frac{1}{2} \rho H_2 A_2 g - q_2 \left(L_6 + \frac{1}{2} L_5 \right) = \frac{1}{2} \rho h_2 A_2 g \tag{8}$$

$$h_{22} = H_2 - \frac{q_2 (2L_6 + L_5)}{\rho A_2 g} \tag{9}$$

$$h_2 = \frac{h_{21} + h_{22}}{2} \tag{10}$$

2.3 Theoretical Calculation of Water Flowing Height of Traditional Roof

The mining coal seam of Yuncheng Coal Mine belongs to near-horizontal thick coal seam. Under this condition, due to the gravity of roof stratum, the central part of the pressure is very strong, and the

Fig. 3 Stress distribution map of long coal face in thick coal seam

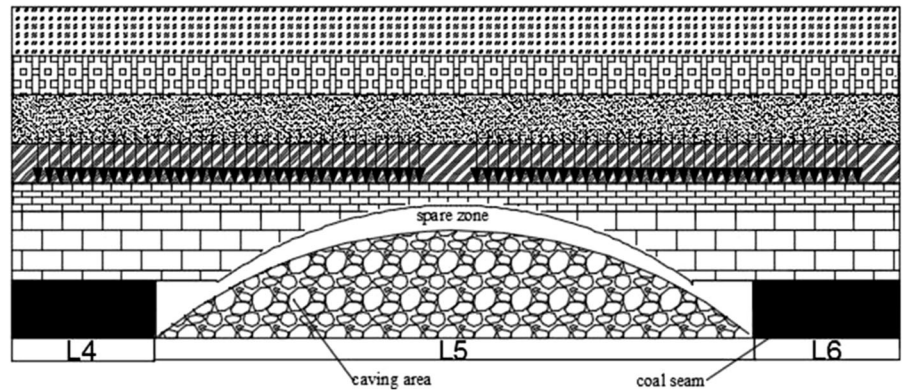
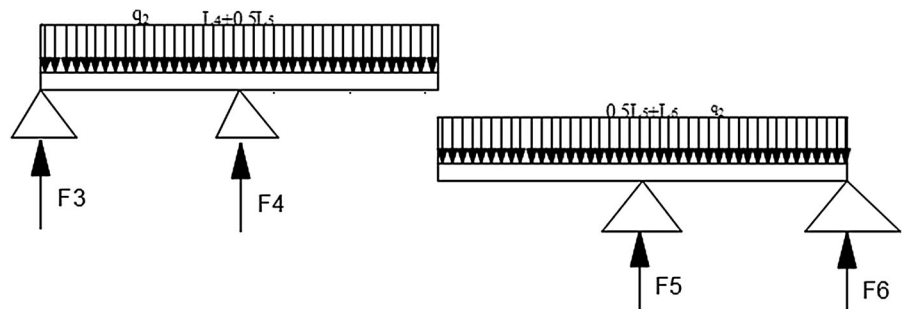


Fig. 4 Simplified mechanics model for short working face in thick coal seam



fracture development presents saddle shape, and the direction of strike and inclined direction of fracture development is roughly the same. The shape of the caving zone is the same as that of the fracture zone.

The upper three zones are formed above the goaf after the roof strata are destroyed. The caving zones and fracture zones are the artificial water diversion channels formed by mining failure. When it affects the goaf above the goaf water, aquifer or goaf water accumulation, that is, the height of water conduction fracture zone is greater than the distance between surface water or aquifer and the mining face, it will cause water inrush from the roof. The empirical formula method can be used to determine the failure height of the roof. Because the coal seam is thick coal seam and the lithology is medium stable, the empirical formula is:

$$H_m = \frac{100 \sum M}{4.7 \sum M + 19} + 2.2 \tag{11}$$

$$H_{li} = 20 \sqrt{\sum M + 10} \tag{12}$$

where M is thickness of coal seam, where H_m is roof failure height during thick coal seam mining, where H_{li} is top plate failure height in gently inclined thick coal seam mining.

3 Engineering Background

The 1308 working face of Yuncheng coal mine is located in the northern wing of the mining area, and the mining depth is between – 800 and – 900 m. The roof of three coal seam is mainly composed of middle and fine sandstone group, and some siltstone and mudstone group can be found locally. The average coal thickness is 7.03 m, the coal seam dip angle is below 8°, containing two layers of gangue, the first layer of gangue from the roof of the coal seam 2.4 m, 0.03 m thick, for sandy mudstone; the second layer of gangue from the bottom of the coal seam 0.36 m, 0.15 m thick, for sandy mudstone. Influenced by mining, it is easy to cause coal seam rib and roof caving. According to the regional hydrogeological data, combined with the analysis of hydrogeological data revealed by the actual borehole in the mine field,

the roof of coal seam 3 is threatened by goaf water and other abundant water sources. During the mining process, the roof is broken and caved, forming the “upper three zones”, which threatens to permeate water. Therefore, it is of great significance for safe mining of coal seam to study the roof failure characteristics and treatment schemes of 1308 working face with three coal seams in deep mining.

4 Numerical Simulation

4.1 Numerical Calculation Model

According to the mining parameters provided by the geological data of the mine and the characteristics of the roof rock, the length, width and height of the model are set to 200 m × 200 m × 200 m; the front, rear, left and right boundaries of the model are set as horizontal constraints, the upper boundary is a free boundary, and the bottom boundary is Fully constrained; coal mining height is 7.3 m, working face length 100 m, along the length of the strike to excavate 10 m per step, a total of 10 steps of excavation. Considering the boundary effect, the left and right boundaries of the coal column distance model for open cuts and stop lines are 50 m; the distance between the protection pillars of the roadway and the front and back of the model is 50 m. Flac3d three-dimensional numerical analysis model shown in Fig. 5.

4.2 Analysis of Simulation Results

The model adopts the elastic–plastic constitutive model and follows the Mohr–Coulomb failure criterion. With the advancing of the working face, the stress of overlying strata redistributes, and the roof overburden

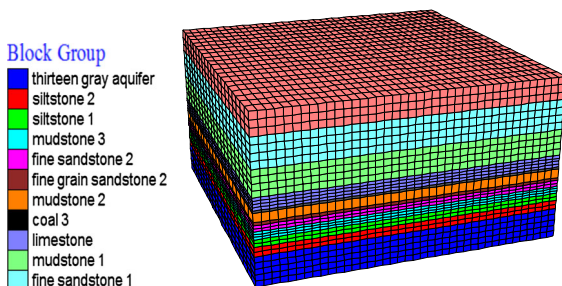


Fig. 5 Working face of 1308 three dimensional numerical calculation model

is destroyed, forming a water-conducting fracture zone. According to the measured rock mechanics parameters of the mine, the mechanical parameters of the top and bottom slate of the coal seam are determined. The shape of plastic failure zone and vertical stress of overlying strata under the condition of 40 m, 60 m, 80 m and 100 m advancing distance of working face are simulated respectively, and the distribution of water conducting fracture zone height of overlying strata in fully mechanized caving face is obtained.

- (1) According to numerical simulation, the vertical stress cloud map of roof under different advancing distance is obtained (Fig. 6).

From the analysis of Fig. 6, it can be seen that the stress area around the stope increases continuously and the vertical stress concentration area is near the cut hole and working face. With the development of mining, the vertical displacement decreases gradually with the increase of the distance from the roof of the coal seam, the stress at the initial mining position begins to decrease, and the vertical stress of the roof also decreases. The stress on the working face gradually decreases.

When the working face is pushed to 80 m, the stress range is not increased and basically remains unchanged; when the working face is pushed to 100 m, a saddle-shaped stress zone is formed. By observing the simulation process, it is found that the top 35 m of the goaf roof is most affected by mining. When the working face advances to about 85 m, the top failure is most serious, especially the water inrush accident.

Cloud chart of plastic failure zone of mining roof plate (Fig. 7).

There was no caving and cracks in the initial roof. When mining was carried out to 10 m, the roof began to collapse in large scale and formed the “upper three zones”. With the increase of the depth of roof failure, when the working face is pushed to 80 m, the plastic depth of roof failure reaches the maximum value, the maximum value is about 53 m, and the plastic depth of roof failure does not increase with the continuous advance of the working face.

- (2) Fracture height analysis

As shown in Fig. 8, when the working face is pushed to the vicinity of 80 m, the overlying strata fissure develops to 53 m. With the further advance of

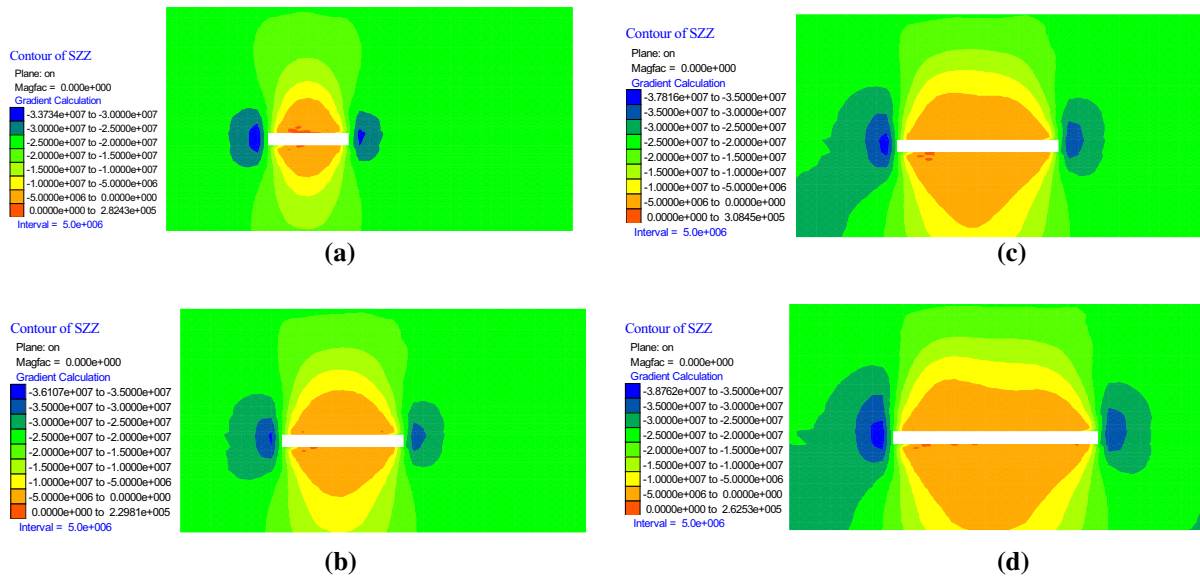


Fig. 6 Vertical stress of mining roof. **a** Work face advancing 40 m, **b** work face advancing 60 m, **c** work face advancing 80 m, **d** work face advancing 100 m

the working face, it can be seen that the overlying strata fissure basically does not expand in the vertical direction, and the height of fissure development basically assumes a straight line after that. Therefore, the height of fissure zone developed by FLAC3D numerical simulation is 53 m.

5 Borehole Segmented Water Injection Test Method

5.1 Introduction to Measured Methods

The variation of fracture development height before and after filling was measured in 1308 working face by drilling and water injection test. The device can plug and inject water into roof perforation at any angle. According to the leakage measurement of water injection, the development of fractures can be determined, and the effect of opening and filling grouting can be further determined.

The height of water-conducting fracture zone determined by numerical simulation is 53 m. In addition, the roof of working face belongs to medium hard and soft rock stratum, and the thickness of coal seam is 7.3 m at the observation section of water-conducting height. Generally, the ratio of water-conducting to mining thickness of medium hard rock

stratum roof is 8–12, so the height of fracture development is estimated to be 56 m. Drilling the front hole at 45 degree elevation and drilling holes and grouting observation holes at 60 degrees.

5.2 Observation and Analysis

Observation results and analysis of failure height of 4.2 roof overburden. The leakage height map of overburden failure is drawn according to the measured data (Fig. 9).

1. ^{1#} Pre-mining hole: Through the leakage map, we can see that the leakage is very small in the upper 80 m range, which shows that the roof overlying strata is a complete rock mass, can be used as a post-mining hole and grouting observation hole contrast hole.
2. ^{2#} post-mining hole: within the range of 10–40 m, the leakage is very large, the maximum leakage is about 15 m, and the fracture affected by mining is larger. The amount of leakage in 0–55 m is much larger than that observed by grouting and before drilling. It can be considered that the largest water diversion fracture before grouting is near 55 m.
3. ^{3#} grouting observation hole: compared with the leakage of the post-mining hole, the leakage of the observation hole after grouting is greatly reduced,

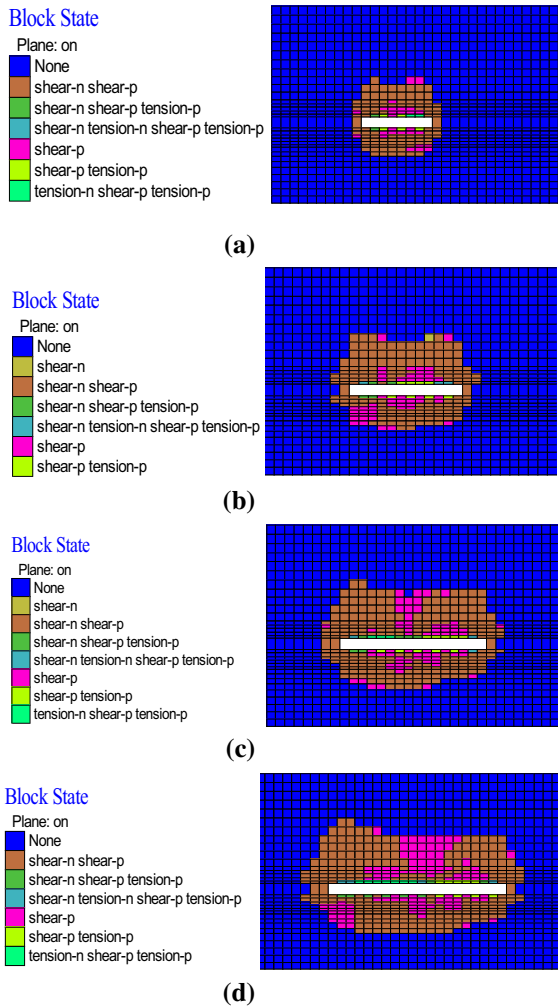


Fig. 7 Plastic failure zone of mining roof. **a** Work face advancing 40 m, **b** work face advancing 60 m, **c** work face advancing 80 m, **d** work face advancing 100 m

and the leakage of the two holes is basically the same as that of the pre-mining hole. In a word, after grouting and filling, the influence of deep mining on rock formation is weakened, and the height of fracture development is greatly reduced.

6 Filling Mining with Super High Water Material

6.1 Slurry Preparation

The roof strata will produce a large number of cracks because of mining, and the grouting plugging of the main cracks will play a better role. Ultra-high water

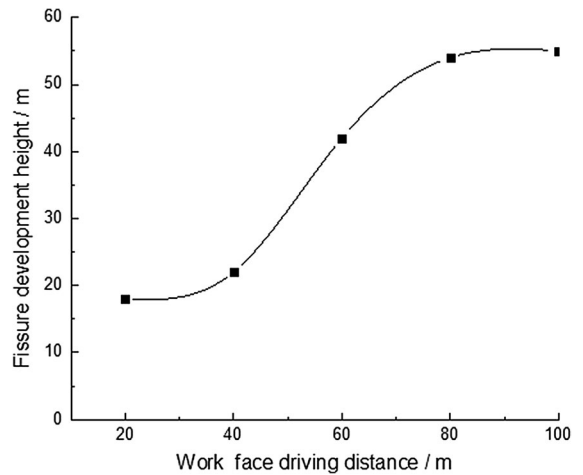


Fig. 8 Diagrammatic sketch of numerical model

material is used in this filling. Ultra-high water material refers to the high water material whose water volume is above 95% and the maximum is 97%. It is mainly composed of two kinds of materials, A and B, which are added 8–11 times water respectively. When filling, they are used in proportion to A:B = 6.4:4.3, and the water cement ratio is 2.4:1.

6.2 Filling Grouting Process

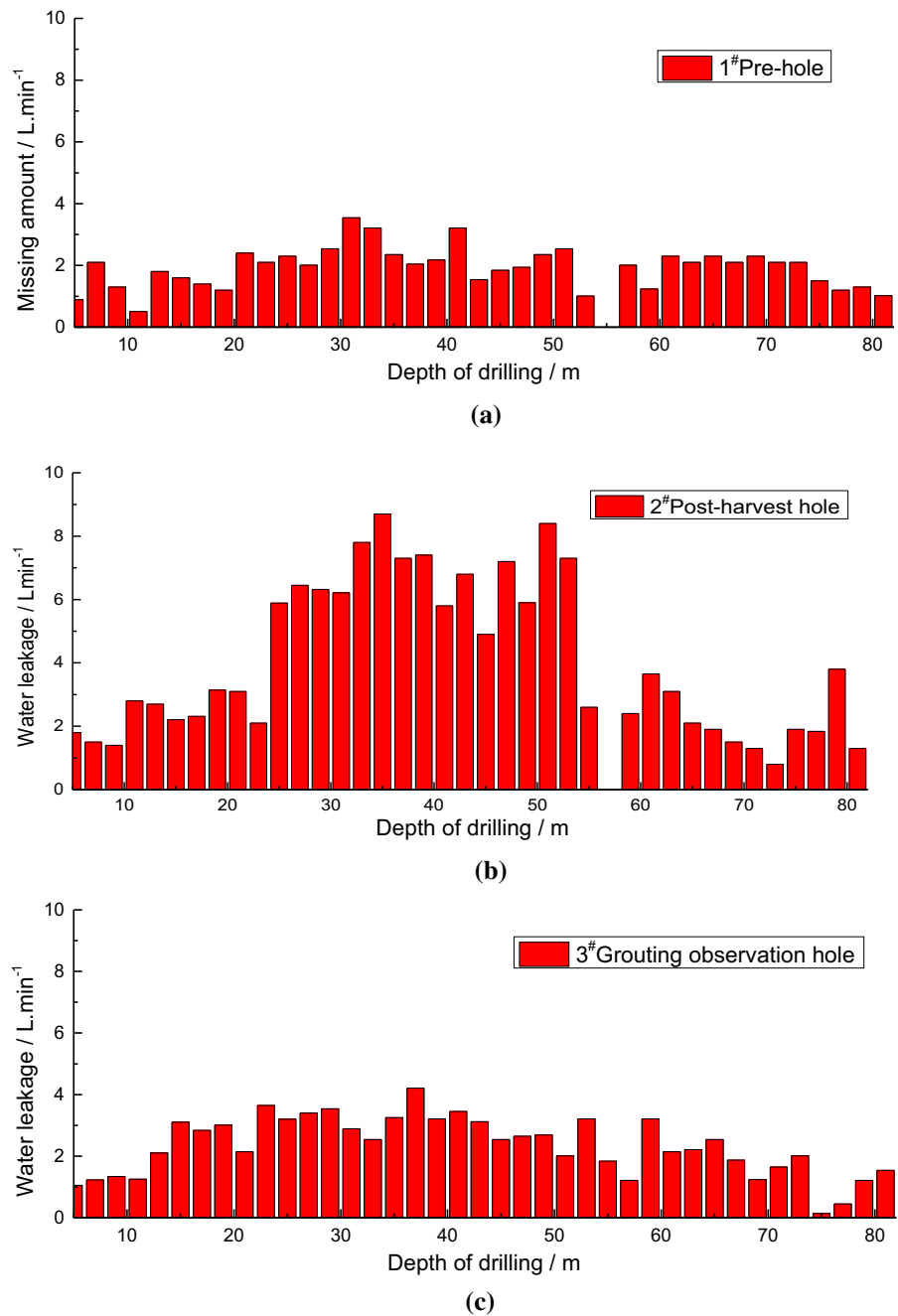
According to the surrounding rock geological conditions and production capacity requirements, the filling process system is arranged underground. The layout is shown in Fig. 10.

Before grouting, fill up the grouting hole, first of all, water injection to see whether the grouting channel is smooth. Then start grouting, in the early grouting slurry more water content, until the grouting stability after the return to normal concentration. The grouting is stopped after a period of time, so that the injected slurry is solidified and blocked at the bottom of the crack. Then continue to start grouting and stop grouting when it is found that the slurry is overflow. After grouting, cement grouting is used to seal grouting holes.

6.3 Filling Effect Analysis

The position of super-high water material flow in the area filled with roof is changing constantly. According

Fig. 9 Observation of water leakage of roof drilling



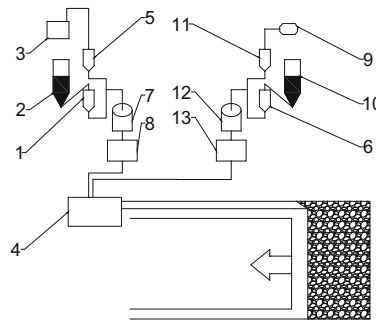
to the flow process, the roof area is divided into 3 filling areas and 4 slurry curing stages.

1. The three filling areas in roof area are initial filling area, completion filling area and end filling area. The superhigh water filling material in the roof area is solidified gradually. According to the

different curing process, it is divided into four stages, namely, initial setting stage, transition stage, basic curing stage and curing stage.

2. Ultra-high water filling material which fills the lower fracture can not be temporarily filled into the upper stratum fissure (above the slurry level),

Fig. 10 Schematic diagram of filling system. 1, 6, 11—Measurement screw; 2, 10—cement warehouse; 3—A material pool; 4—AB material mixing tank; 5—electronic belt weigher; 7, 12—water reservoir; 8, 13—stirring pool; 9—B material pool



1,6,11-Measurement screw 2,10-Cement warehouse 3-A material pool 4-AB material mixing tank 5-Electronic belt weigher 7,12- Water reservoir 8,13- Stirring pool 9-B material pool

but the roof of the mining area will collapse because of the development of fissures or some factors. As the slurry level rises, previously unfilled cracks will be filled by slurry in the later filling, so filling super-high water material can plug the cracks.

7 Conclusion

1. According to the theory of material mechanics, the mechanics model of thick coal seam mining is established. The short working face of thick coal seam is simplified as simply supported beam on both sides, and the long working face of thick coal seam is simplified as two symmetrical extended beams. According to the theory of semi-infinite body, the failure heights of overlying rock after mining in short working face of thick seam and long working face of thick seam are calculated respectively. Compared with the traditional formula, the mechanical calculation model is more close to the measured result.
2. According to the actual geological data of 1308 working face in Yancheng Coal Mine, the corresponding numerical model is established, and the failure height of overlying rock is simulated by FLAC3D. The results show that the simulation results are slightly lower than the empirical formula and are closer to the field measurement.
3. By using super-high water material to fill the goaf in thick seam, on the one hand, effective filling is added on the basis of natural filling rate, on the other hand, the number of caving cycles is

effectively reduced, and the height of overburden failure is prevented and controlled. Therefore, filling with super-high water material has great application value to reduce the height of overburden failure and the threat of roof permeability in thick coal seam mining.

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