

Motion model and key parameters of overburden strata in longwall filling face

Zengde Yin ^{1,3,*}, Jinxiao Liu ^{2,3,4}, Feng Zhang ², Yongle Liu ², and Wenxin Li ^{2,3}

¹ College of Safety and Environment Engineering, Shandong University of Science and Technology, 579 Qianwangang Rd, Huangdao District, Qingdao 266590, China

² College of Energy and Mining Engineering, Shandong University of Science and Technology, 579 Qianwangang Rd, Huangdao District, Qingdao 266590, China

³ Mine Disaster Prevention and Control-Ministry of State Key Laboratory Breeding Base, Shandong University of Science and Technology, 579 Qianwangang Rd, Huangdao District, Qingdao 266590, China

⁴ Key Laboratory of Deep Coal Mine Excavation Response & Disaster Prevention and Control, Anhui University of Science and Technology, Huainan 232001, China

Abstract: When the paste material is filled into the longwall working face of the coal mine, it firstly controls the movement of the overburden strata, thereby limiting the movement of the far field rock layer and reducing the subsidence. With this regard, the paste filling technology of the long-wall mining can address the limitation of "three down, one up" (mining under water body, building and rail, and on karst water body) technology in coal mining, thus improving the extraction rate of coal resource. To control the movement of the overburden strata near the working face, the prerequisite is to clarify the relationship among the parameters, including coal mining thickness, filling body thickness, filling step, filling body strength, etc. On this basis, this paper established an overall mechanical model of the filling body and surrounding rock, and determined the key technical parameters of the overburden movement, i.e., the filling rate, the strength of the filling body, and the filling step. Then, the influence of these parameters on the overburden movement and abutment pressure was analyzed through the numerical simulation method. The results show that at a higher filling rate, the overburden motion can be better controlled; the filling step only had a significant effect on the roof subsidence within the relevant step; as the early strength of the filling body was higher, the overburden subsidence was smaller and the abutment pressure in front of the face was better controlled. The research of overburden motion model and its key parameters have a good guiding significance for paste filling in the longwall face of coal mines.

*Corresponding author: skd993938@sdust.edu.cn

1 Introduction

Back filling technology has been applied in mining industry for over 100 years. In the 1930s, the application of back filling appeared in non-coal mines [1, 2]. The development of backfilling technology has obtained considerable development from non-cemented filling to cemented filling. Paste filling technology originated from the lead-zinc mine in Badglund, Germany in the early 1980s. In 1991, paste filling technology was first applied to coal mines by the German Mining and Metallurgical Technology Company.

As the paste material has the characteristics of high concentration, no precipitation, no dissociation and no water secretion, it can well control the movement of overburden rock [3, 4], and can address the limitation of "three down, one up" [5, 6] coal compaction. As a result, the paste filling technology could improve the extraction rate of coal resources, and extend the service life of the mine, which contribute to its rapid promotion [7-10]. In 2006, the Taiping Coal Mine in Shandong Province of China used paste filling in layered mining in thick coal seams, and achieved excellent economic benefits. Since then, a large number of coal mines such as Xingtai Coal Mine and Daizhuang Coal Mine have successively applied paste filling technology.

The goaf in coal mine requires a large amount of paste filling materials to be completely filled. In China, coal gangue [11], Yellow River sand, etc. are used as the main material for the paste filling. Additionally, an appropriate amount of fly ash is added to increase its fluidity, the concrete is used as the cementitious material. Finally, the appropriate amount of additives contribute to form a paste filling material with certain properties (early strength, fluidity, delamination and condensation duration) [12-14].

Whether the longwall face in coal mines [15] is filled with pure gangue [16-19] or paste, the procedure of filling right after mining always exists. That is, after extracting at the face, it needs to be filled before overburden rocks are collapsed. Only in this way, the mining space can be filled to the greatest extent, and the movement of the overburden strata can be controlled properly [20, 21]. As a result, the subsidence can be reduced [22]. So, it is necessary to aware the relationship among coal mining thickness, backfill thickness, backfill step, backfill strength and other parameters that related to the effectiveness of overburden motion control. On this basis, we first established the overall mechanical model of the filling face and obtained the main technical parameters, and then investigated the influence of these parameters on the overburden movement and abutment pressure by numerical simulation [23, 26].

2 Establishment of mechanical model and parametric analysis

2.1 Motion control model of overburden rock with longwall paste filling face

As the filling materials participate in the self-organized overburden movement of longwall working face, it changes the overburden structure [27] and movement mode. Thus it makes the mechanical model of the filling face different from that of the support-surrounding rock. Based on the impact degree of each involved component, as shown in **Figure 1**, the overall mechanical model of "surrounding rock - filling body - support" was established. The basic unit of the mechanical model of the filling face mainly includes the following components: ① Overburden rock. Due to the limited movement space, the overburden in the filling working face basically does not form of a rock beam, but in the form of a "plate" and "shell" [28]. ② Filling body. The filling body can timely control the subsidence of overburden. ③ Support. The cyclic pressure [29] of filling face is not obvious, thus the support is subjected to relatively small forces and basically not affected by dynamic loads. ④ Floor. The heaving floor [30] occurs less in the filling face than that in the ordinary mining face.

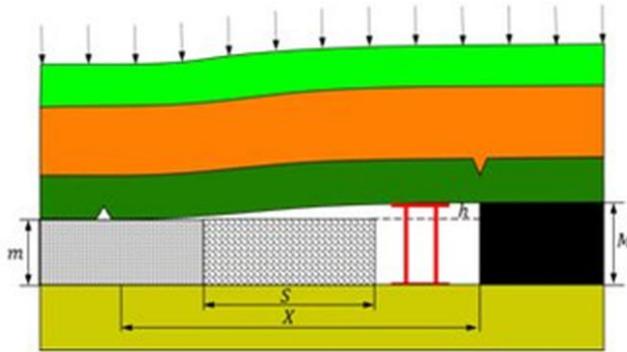


Fig. 1. Mechanical model of "surrounding rock-filling body-support"

According to the stress distribution and structural characteristics of each unit in the mechanical model of the filling face, it can be simplified to the corresponding force receiver. The overburden can be simplified as a rigid body, which plays a leading role in the entire mechanical model, and the force of the entire system is determined by the overburden. The filling body exists as a complete cement in the working face, so it can be simplified as an elastic body. The filling body has two roles. One is to control the continued subsidence of the overburden, and the other is to transmit the force of the overburden to the floor to limit its deformation. Considering the starting-up condition of the safety valve, the support [31] can be considered as an elastic-slip body. The support in the filling face has two main functions. One is to limit the subsidence of the overburden, allowing the overburden to exist in a higher position and improving the filling rate of the working face. The other is to control the rock pressure activity of the filling face. The floor can be simplified as a rigid body, which is under passive stress in the system.

2.2 Key parameters of overburden rock movement

The control quality of overburden movement in filling face is mainly determined by following factors: the filling effect, filling body property, overburden rock property, filling process and the interaction between them. The filling effect mainly refers to the filling rate of the working face. At a higher filling rate, the movement space of the overburden rock is smaller and the amplitude of the movement is decreased. The property of the filling body mainly refers to its strength. As the strength of the filling body gets greater, its ability to resist deformation under load is stronger, the position of the overburden is higher, and overburden movement control is better. The property of overburden rock mainly refers to its strength. With high strength, it the overburden rock has large resistance to deformation, which means the pre-filling subsidence of overburden rock would be small, and the filling rate of goaf would be higher. The filling process mainly refers to the filling step, which is the distance to the primary filling along the working face. At a larger filling step, the overburden has sufficient subsidence time, the amount of subsidence is greater, and the filling rate in the goaf is reduced. However, if the filling step is smaller, the number of filling cycles will be increased, which is not conducive to production. Therefore, the filling step must be reasonably selected according to the geological and production conditions. The general working face is filled once every 3 to 5 cycles of mining, that is, the filling step is about 2 to 4 m.

From the above analysis, we conclude that the key parameters of the movement control of the overburden rock in the filling face include filling rate, filling body strength, filling step and overburden strength. Under a certain engineering geological conditions of a mine, the overburden strength is constant. The other three parameters change accordingly due to

the changes in external factors such as filling process and construction process. The parameters of overburden rock motion control are not independent, but interact and have a certain relationship with each other.

Before the paste is filled, the overburden rock has a certain amount of subsidence. During the production process, the filling always lags behind the extracting face by a certain distance, and the roof is usually exposed. It is difficult for the support to prevent the movement of the upper strata before the equilibrium is achieved. The subsidence amount overburden rock due to this lag can be called the amount of roof subsidence before filling (h_1). Owing to the particularity of the mining operation, it is difficult to ensure that the top of the filling body and the roof are completely in contact during the filling process. As a result, after the filling is completed, the distance between the roof and the top of the filling body is called the underfilled amount (h_2). Depending on the relationship with the filling body, the sum of the underfilled amount and the amount of roof subsidence before filling is referred to as the amount of uncontacted overburden subsidence (**Eq.2**).

The compression ratio of the filling body is not only affected by its own properties including the particle gradation, water secretion, etc., but also related to the pressure of the surrounding rock. In general, the compression ratio of the paste cements filling is less than 5%.

Although there is a certain amount of bending and sinking of the roof before paste filling, it is required that the roof should not collapse before the filling process [32]. Therefore, after a certain filling step, the roof could gradually sink and contact the filling body.

From the overall mechanical model of "surrounding rock - filling body - support" in the working face, the relationship among the control parameters of overburden rock motion in the filling face can be obtained, as shown in the following equations:

$$M = m + h \quad (1)$$

$$h = h_1 + h_2 \quad (2)$$

$$n = \frac{m}{M} \quad (3)$$

$$w = h + f \cdot m \quad (4)$$

$$X \geq S \quad (5)$$

where M is the thickness of coal seam in the unit of m; m is the filling height in the unit of m; h is the uncontacted overburden subsidence rock in the unit of m; n is the filling rate; X is the distance from the coal wall to the roof-paste contacting position in the unit of m; S is the filling step in the unit of m; w is the final subsidence of overburden in the unit of m; and f is deformation coefficient of the filling body.

3 Simulation on movement parameter of overburden rock

3.1 Establishment of numerical model

This simulation is based on the condition of 2351 longwall filling face in Daizhuang Coal Mine of Shandong Zibo Mining Group. The length, width and height of the three-dimensional calculation model were set to 200 m, 100 m and 47.5 m, respectively. The model contained 207,500 hexahedral element grids and 243,104 nodes. The lateral and bottom boundary of the model constrained the normal displacement, and the top boundary

replaced the weight of the overburden rock layer with a uniform load of 10MPa. The Mohr-Coulomb yield criterion was used for the simulation. The rock mechanical parameters of the coal seam and different rock layers were determined according to the test results of the rock core, as shown in **Table 1**.

Table 1. Rock mechanical properties

Property	Thickness /m	Bulk /Gpa	Shear /Gpa	Friction /°	Tension /Mpa	Density /(kg/m ³)	Cohesion /Mpa
Siltstone	9.0	1.2	0.6	38	7.4	2500	3.2
Mudstone	7.0	1.3	0.5	35	3.0	2400	1.2
Siltstone	2.0	1.5	0.8	37	4.6	2200	2.7
Fine-sandstone	1.5	1.3	0.7	35	6.2	2300	3.0
Medium-sandstone	7.0	2.2	1.2	42	12.0	2500	4.6
Siltstone	3.0	1.5	0.8	35	4.2	2100	2.4
Fine-sandstone	1.5	1.2	0.5	30	7.6	2300	3.4
Siltstone	2.0	1.0	0.5	33	4.6	2500	2.7
Coal	2.5	0.52	0.2	18	0.9	1400	0.5
Clay	4.0	1.8	0.7	30	5.4	2400	3.8
Siltstone	8.0	2.2	1.2	48	8.9	2600	4.1

3.2 Parameter setting of filling body in numerical simulation

After the paste material in the goaf is condensed and solidified to form a filling body with certain strength, its property is not constant, but varying with the pushing of the mining face and the increase of the curing age. In this simulation, step-by-step excavation is adopted, excavating 4 m at a time. This distance represents the daily advance distance of the working face, and also serves as the filling step. In this way, the excavation step, the advancement distance, and the filling step correspond to each other one by one, and their values are consistent.

Table 2. The strength of paste material with different curing age

Curing age	8h	1d	3d	7d	28d
Compression	0.22	0.52	1.03	1.27	1.78

Based on the optimal ratio of the compressive strength of the paste material to the curing age [33], as shown in **Table 2**, the nonlinear fitting equation was applied to establish, as shown in **Equation (6)**. In this way, a one-to-one correspondence between the compressive strength of the filling body and the filling step was established. In this simulation, the tensile strength was set to one-tenth of the compressive strength. The FLAC-3D simulation was used to analyze the gradual change process of the strength with the advance of the working face.

$$F = 0.72(t - 0.3)^{0.25} \quad (6)$$

where t is the curing age in the unit of d.

According to the experimental results, we found that other parameters of paste filling materials did not change significantly with the change of curing age, and were set as constants in the simulation.

The main influencing parameters for the overburden movement include the filling rate, the strength of the filling body and the filling step of the working face. If all these three factors are considered in the simulation, it is difficult to find the varying pattern. Thus, in this simulation, a single factor method was used to study the influence of each factor on the overburden movement and abutment pressure. In order to simplify the simulation process, the impact of the initial mining was not taken into account.

4 Analyzing results

4.1 Evolution law of overburden movement and abutment pressure at different filling rates

In the analysis on the evolution of overburden movement and abutment pressure at different filling rates, it was assumed that the strength of the filling body conformed to the variation law of **Equation (6)**, and the influence of the filling step was not considered. **Figures 2-4** show the three-dimensional abutment pressure distribution of the stope when the working face is advanced to 80 m at different filling rates (90%, 80% and 70%). It can be seen that at a same filling rate, the abutment pressure in the filling body grows with the increase of the distance from the filling body to the extracting face. In addition, at a lower filling rate, the abutment pressure on the filling body gets smaller, and the filling body has poorer performance in controlling the movement of overburden rock.

Table 3 shows the distribution characteristics of the maximum abutment pressure of surrounding rock at different filling rates. The maximum value and concentration coefficient of high abutment pressure vary greatly at different filling rates. Through linear regression analysis, when the filling rate changed by 10%, the maximum abutment pressure changed by 21%. As the advancement of the working face, the range of the maximum abutment pressure changed accordingly. When the filling rate was 90%, the maximum abutment pressure was 14.1MPa and obtained at the location of 3.0 m in front of the working face. When the filling rate was 80%, the maximum abutment pressure was 16.2MPa, which is located 4.5 m in front of the working face. As the filling rate was 70%, the maximum abutment pressure was 18.3MPa, 6.4 m to the working face.

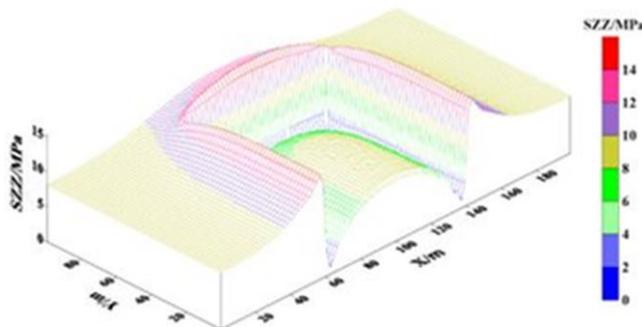


Fig. 2. Distribution of abutment pressure at filling rate of 90%

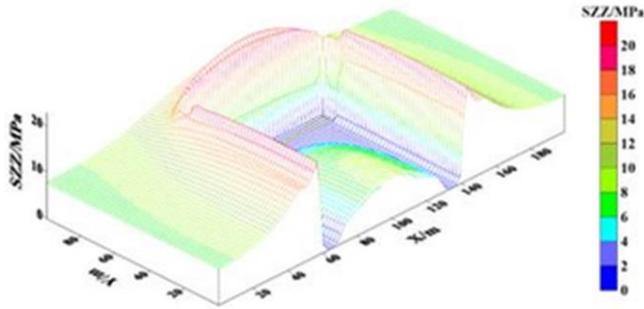


Fig. 3. Distribution of abutment pressure at filling rate of 80%

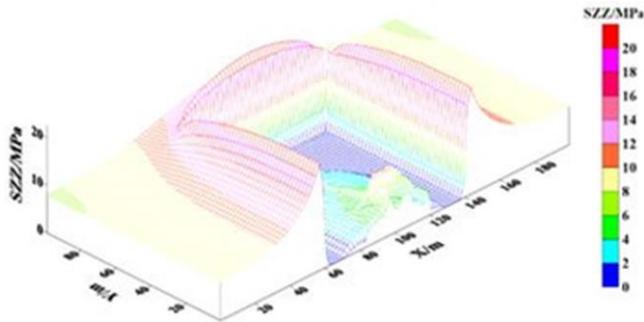


Fig.4. Distribution of abutment pressure at filling rate of 70%

Table 3. Characteristics of the abutment pressure and deformation at different filling rates

Filling rate	Maximum abutment pressure			Deformation of overburden rock and filling body		
	Maximum value /MPa	Concentration factor	Distance to working face /m	Theoretical value /m	Observed subsidence /m	Deformation of filling body /m
90%	14.1	1.50	3.0	0.25	0.272	0.022
80%	16.2	1.69	4.5	0.50	0.515	0.015
70%	18.3	1.91	6.4	0.75	0.760	0.010

A X-Y slice at the position of 0.5 m above the coal seam was extracted to plot the contours of overburden subsidence at different filling rates, shown as **Figures 5-7**. And the maximum deformation characteristics of the overburden rock and the filling body are listed in **Table 3**. At a same filling rate, the subsidence of the overburden rock gradually increases from the working face to the goaf. In addition, the subsidence of the overburden movement

gradually decreases as the filling rate increases. When the filling rate is 70%, 80% and 90%, the maximum subsidence is 0.76 m, 0.515 m and 0.272 m, respectively. According to the results of linear regression, when the filling rate varied by 10%, the maximum subsidence value of the overburden varied by 24.4%. Through data analysis, it was found that the location of the maximum subsidence value occurred in the middle of the working face (tendency). At a higher filling rate, the filling body contacts the overburden earlier, the overburden force is greater, the deformation of the filling body is greater, and the control effect of the overburden subsidence is better.

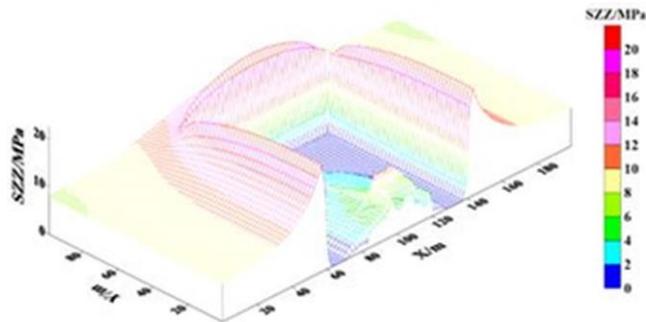


Fig. 5. Vertical displacement distribution of overburden at a filling rate of 90%

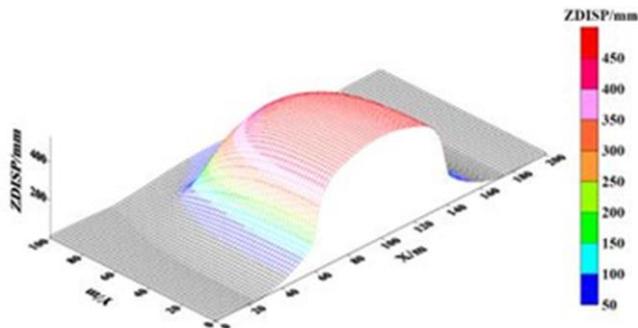


Fig. 6. Vertical displacement distribution of overburden at a filling rate of 80%

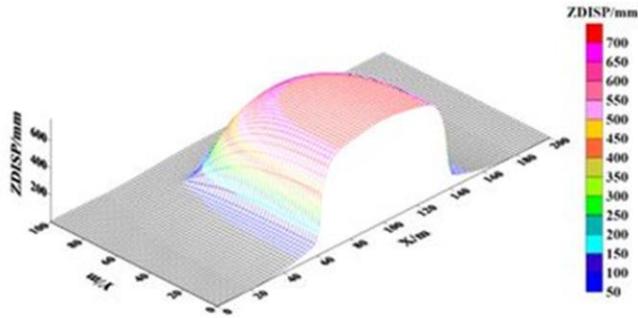


Fig. 7. Vertical displacement distribution of overburden at a filling rate of 70%

4.2 Evolution law of overburden movement and abutment pressure at different filling steps

In the analysis on the evolution of overburden movement and abutment pressure at different filling steps, it was assumed that the filling rate was 80%, and the compressive strength of the filling body conformed to the variation law of **Equation (6)**. **Figures 8-10** show the abutment pressure profiles along the advancing direction in the three-dimensional model at 80 m. Shortly after the working face is pushed forward, the filling body limits the movement of the rock layer, causing stress in roof, filling body, and floor. Finally, the stress values in roof, floor and filling body at a certain position behind the working face are gradually converging.

It can be seen from **Figures 8-10** and **Tables 4-5** that with different filling step, the high abutment pressure in front of the working face and the low abutment pressure in the filling body both show certain variation patterns. At a larger filling step, the peak of high abutment pressure in front of the working face is larger and farther away from the coal wall. While the change in the high abutment pressure is smaller, not more than 3%. In contrary, the low abutment pressure at same distance behind the working face decreases more than 10% with the increase of the filling step.

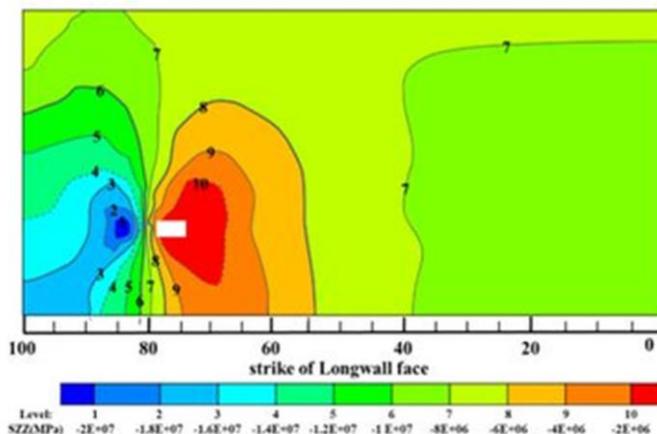
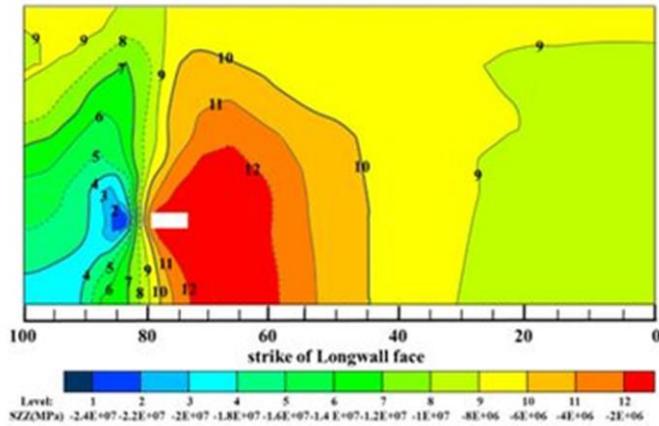
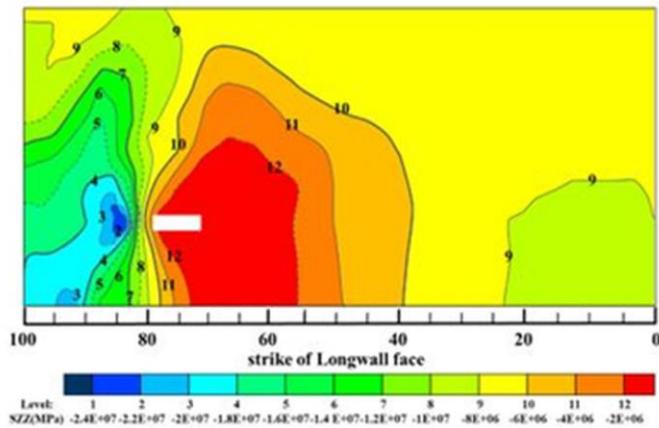


Fig. 8. Distribution of abutment pressure at the filling step of 4 m**Fig. 9.** Distribution of abutment pressure at the filling step of 6 m**Fig. 10.** Distribution of abutment pressure at the filling step of 8 m**Table 4.** Distribution characteristics of high abutment pressure in front of working face

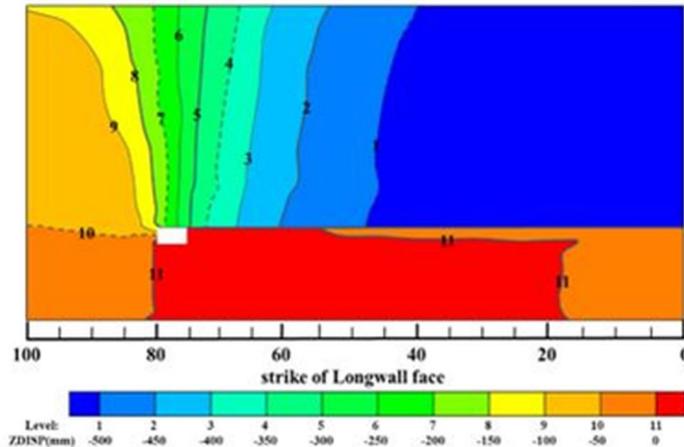
Filling step	Maximum value /MPa	Distance from coal wall /m
4m	19.58	+3.24
6m	19.95	+3.35
8m	20.43	+3.42

Table 5. Distribution characteristics of low abutment pressure behind the working face

Filling step /m	abutment pressure value of filling body (MPa) at different distance from coal wall			
	10m	20m	30m	40m
4	1.6	4.21	6.42	8.54
6	1.24	1.98	4.45	6.27
8	0.95	1.23	2.62	3.92

Figures 11-13 are vertical displacement profiles of the 3D model along the advancing direction. It can be seen that the change in the filling step has a large influence on the displacement of the roof only within 10 m behind the coal wall. The subsidence of the roof beyond 20 m behind the working face is larger than 500 mm and is in contact with the filling body, so it's barely affected by the filling step change.

In the paste filling process, we are concerned with the affect of roof subsidence on the filling effect within the filling step. Therefore, we conducted a comparative analysis. When the filling step was 4 m, the minimum subsidence value of the roof within the filling step was 180 mm and the maximum value was 304 mm. When the filling step was 6 m, the minimum subsidence within the filling step was 200 mm and the maximum value was 350 mm. When the filling step was 8 m, the minimum subsidence was 250 mm, and the maximum value was 410 mm. Therefore, when the filling step was set to different values, i.e., 4 m, 6 m and 8 m, the minimum subsidence value within the filling step changed by more than 10%, while its maximum value changed by more than 15%.

**Fig. 11.** Vertical displacement distribution at the filling step of 4 m

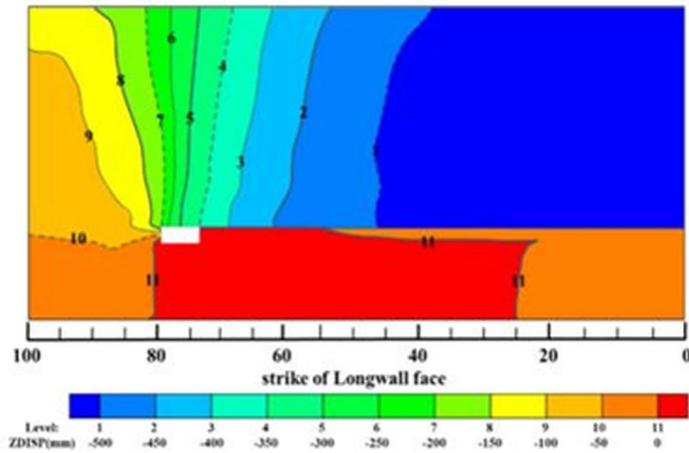


Fig. 12. Vertical displacement distribution at the filling step of 6 m

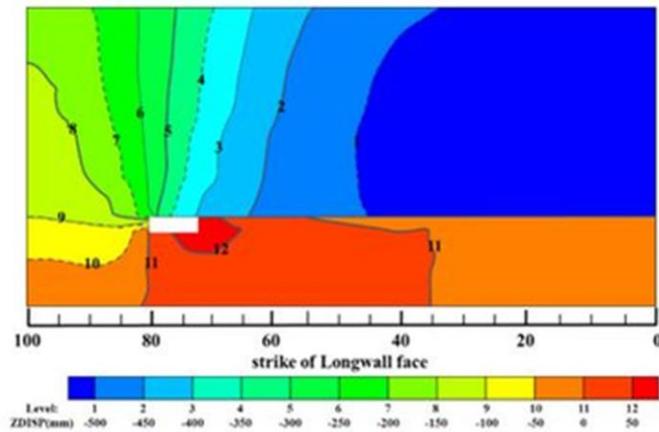


Fig. 13. Vertical displacement distribution at the filling step of 8 m

4.3 Evolution law of overburden movement and abutment pressure at different filling strength

The early strength of the filling body can affect the movement of the overburden rock and it was simulated as well. The paste with higher early strength in Equation (6) is denoted by P_1 . At the same time, we assume a paste with a linear relationship between the strength of the filling body and the curing age, which can be denoted by P_2 . The linear fitting strength of P_2 is $F=0.29+0.05t$. In addition, we also assume a paste material with lower early strength, which can be denoted by P_3 , and its curve fitting strength can be expressed as $F=0.25+0.05e^{0.12t}$. The filling rate of this simulation was also set to 80%, and the filling step was not considered. The relationships between the strength and the curing age for these three paste materials are shown in Figure 14.

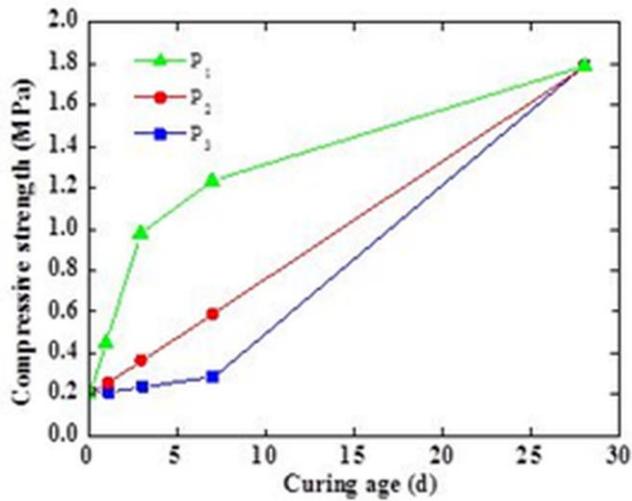


Fig. 14. Relationships between the strength and the curing age for different paste materials

It can be seen from Figures 15-17 and Tables 6-7 that as the strength of the filling body changes, the high abutment pressure in front of the working face and the low abutment pressure in the filling body show certain variation patterns. Different filling body strengths have little effect on the high abutment pressure, and the change degree does not exceed 3%. However, the change in the filling body strength has a great impact on the low abutment pressure. Comparing P₂ (linear filling body strength) to P₁ (high early strength), the difference in the low abutment pressure is under 5%. On the other hand, comparing P₂ with P₃ (low early strength), the difference in the low abutment pressure is above 10%.

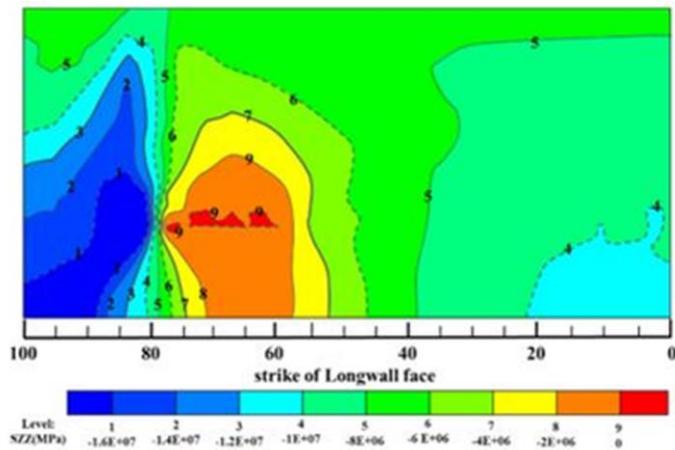


Fig. 15. Distribution of strength and abutment pressure of filling body (P₁)

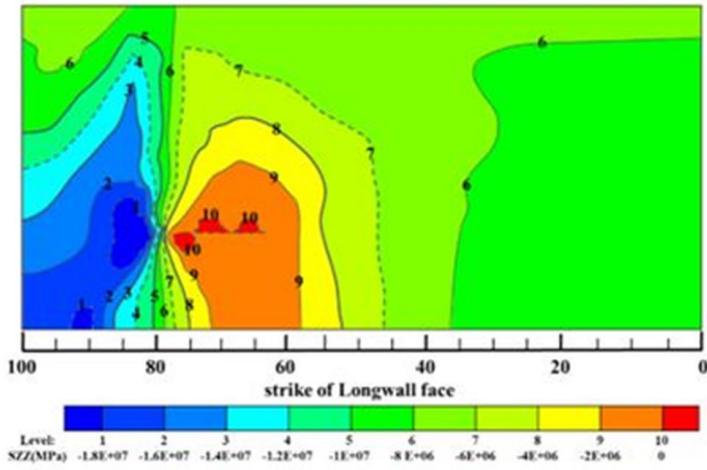


Fig. 16. Distribution of strength and abutment pressure of filling body (P_2)

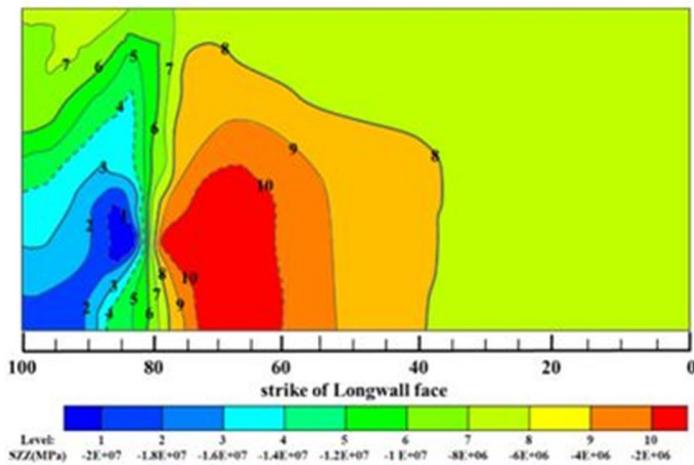


Fig. 17. Distribution of strength and abutment pressure of filling body (P_3)

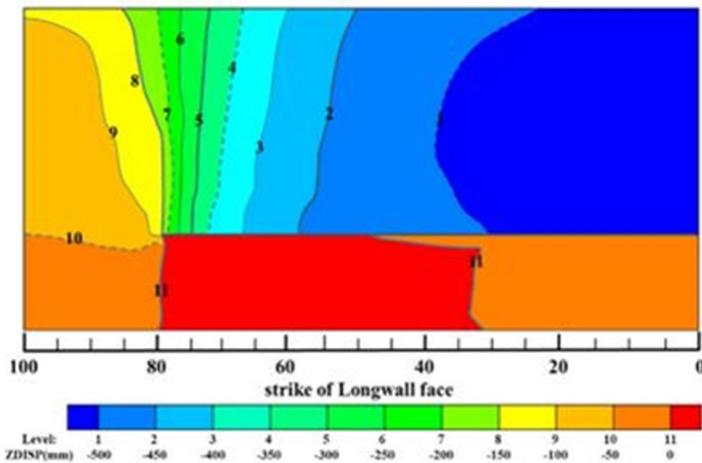
Table 6. Distribution characteristics of maximum abutment pressure in front of working face

Filling strength	Maximum value /MPa	Distance from coal wall /m
P_1	17.88	2.48
P_2	18.32	2.86
P_3	18.73	3.22

Table 7. Distribution characteristics of low abutment pressure behind the working face

Filling strength	abutment pressure value of filling body (MPa) at different distance from coal wall			
	10m	20m	30m	40m
P ₁	1.72	3.48	5.18	6.62
P ₂	1.66	3.36	4.95	6.31
P ₃	1.35	2.77	4.35	5.89

Figures **18-20** are vertical displacement profiles of overburden rock with different filling body strengths. Different filling body strengths only change the subsidence value of the roof within 20 m behind the working face. It can be seen from **Table 8** that when the early strength of the fill is low, its control of overburden movement is significantly less effective than that of high early strength (**P₁**) and that of linear filling body strength (**P₂**). Comparing **P₂** to **P₁**, the variation range of overburden subsidence does not exceed 5% (within 20 m behind the working face). Comparing **P₂** to **P₃**, the variation range of overburden rock subsidence exceeds 10%.

**Fig. 18.** Distribution of vertical displacement at high early strength of the filling body (P₁)

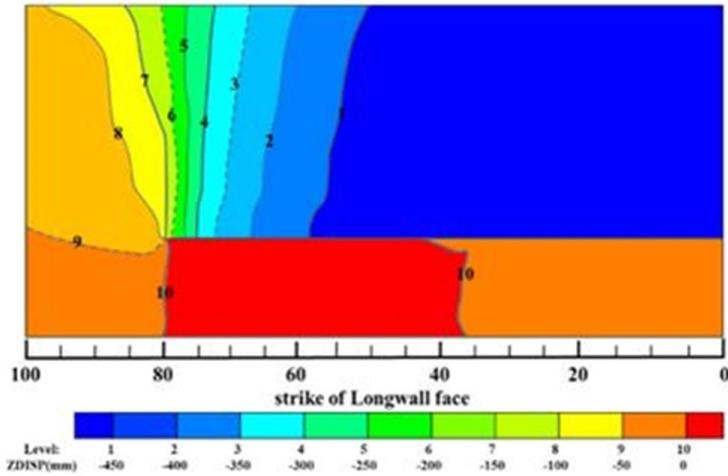


Fig. 19. Distribution of vertical displacement at linear strength of the filling body (P_2)

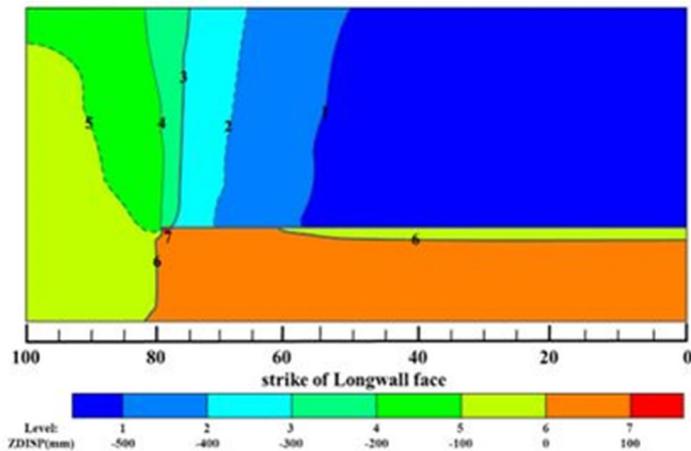


Fig. 20. Distribution of vertical displacement at low early strength of the filling body (P_3)

Table 8. Movement characteristics of overburden with different filling strength

Filling strength	Overburden subsidence value(mm) at different distance from coal wall		
	0m	-10m	-20m
P_1	154	345	424
P_2	160	358	438
P_3	212	405	487

4 Conclusions

(1) The overall mechanical model of the filling body and surrounding rock in the longwall mining was established, and the basic unit of the mechanical model was determined, which included overburden rock, filling body, support and floor. In addition,

the role of the basic unit in the mechanical model was analyzed.

(2) The three key parameters of overburden rock motion in the filling face were determined, which were filling rate, filling step and filling body strength. In addition, the relationship among overburden rock movement parameters of paste filling face was established.

(3) The filling rate had a great influence on the overburden movement and abutment pressure. At a higher filling rate, the control effect on the movement was better. Therefore, in the process of coal mine paste filling, the filling rate is an important parameter to control the overburden movement. Various means should be adopted to increase the filling rate of the stope. The filling step has little effect on the high abutment pressure in front of the working face, but has a great effect on both the low abutment pressure in the filling body and the subsidence of the roof within the filling step. Therefore, in the process of coal mine paste filling, the excessive filling step can cause a very adverse impact on the filling. According to the geological conditions and construction technology, the filling step should be selected as small as possible. Different filling body strengths have a certain impact on the abutment pressure. When the early strength of the filling body is greater, the movement control effect is better. Therefore, in the design of the coal mine paste filling, the bulk material with a high early strength is preferable.

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