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Research Article

Study on the Migration Law of Overlying Rock in the Upward Layered Continuous Mining Face of Thick Coal Seam with Paste Backfill Mining

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With the massive mining of coal resources, coal mining under special conditions such as "Coal mining under buildings and railways and water-bodies" thick coal seams has became a key concern for relevant scholars. As a mining method to effectively replace "Coal mining under buildings and railroads and water-bodies" thick coal seams, paste backfilling is an important part of the coal green mining system. In this paper, by combining theoretical analysis, numerical simulation, and other means, the migration law of overlying rock in paste backfill mining of continuous mining face in thick coal seam upwards under the village was studied. FLAC3D numerical simulation software is used to analyze the upward separation of thick coal seams. Surface subsidence was simulated at each stage of paste backfill mining in the continuous mining face, and the influence of the backfill elastic modulus on the overburden subsidence, the backfill and coal stress, the range of the overlying plastic zone, and the surface deformation was simulated and analyzed. The elastic modulus of the filling body was finally determined.

1. Introduction

China is a big energy-consuming country. Coal resources account for about 93% of China's proven resource reserves. However, with the change of China's primary energy consumption structure, the proportion of coal resources in China's primary energy consumption has gradually decreased, but coal consumption still accounts for 56.8% of total energy consumption. With the massive mining of coal resources, the problem of "Coal mining under buildings and railways and water-bodies" [1–3] has attracted the attention of mining workers. With the rapid increase in the area of construction and transportation, "Coal mining under buildings and railways and water-bodies" has a clear upward trend [4–6]. As a result, a large number of protective coal pillars were left behind. This has become an important issue for sustainable mining of coal resources.

As an important part of the green coal mining system, paste filling technology can not only deal with the problem of gangue accumulation on the surface and improve the recovery rate of coal resources but also effectively control the surface subsidence and protect the surface buildings, so it is widely used in the "Coal mining under buildings and railways and water-bodies" thick coal seams. At present, many scholars have carried out research on paste filling mining technology. Zhou et al. [7, 8] established a technical system for backfilling gobs with high-concentration paste materials. Feng et al. [9–11] established an ultra-high water filling technology system for coal resource replacement through ultra-high water materials. Chen [12] studied the creep hardening characteristics of filling paste by means of uniaxial compression test. Through the gradual decrease of the strain rate of the filling paste in the elastic stage, the increase of the instantaneous deformation modulus, and the creep strength of the filling paste being greater than its uniaxial compressive strength, it is concluded that the filling paste will undergo macroscopic hardening during the creep process. In conclusion, it has important use value to maintain the long-term stability of the filling body and improve the filling effect.

The combined support method proposed by Zhang et al. [13] solved the problem of large deformation of surrounding rock of the roadway when the roadway passes through the goaf. Through a series of laboratory tests such as slump test and rheological test, Feng [14] determined the effect of fly ash content on the long-term stability of the filling paste, top connection performance, and bleeding rate on the basis of comprehensive analysis of rheological properties. Other scholars at home and abroad have carried out a lot of research on filling materials [15–29], filling technology, theory of backfilling body supporting roof, and overlying rock failure mechanism. The existing research results have effectively guided the production practice and at the same time promoted the development of filling mining technology and theory.

2. Engineering Background

In a coal mine in Yulin, Shanxi Province, the average thickness of the main coal seam No. 2-2 is 8.52 m, which is a thicker one in the thick coal seams. Affected by village and town planning, the No. 2-2 coal layer cladding coal resource is about 50 million tons, and the coal mine produces about 1.7 million tons of coal gangue every year. It seriously affects the sustainable development of the coal mine, so the use of paste filling technology to mine is the only way for the sustainable development of the coal mine. After analyzing its mining technical conditions, the thick coal seam layered continuous mining face paste filling technology is selected for mining. At the same time, considering that the coal structure and strength conditions of the No. 2-2 coal seam are better, it is necessary to ensure the roof during the lower layered mining. Therefore, the paste filling mining technology of the upward layered continuous mining face in the thick coal seam is used to recover the coal resources. The principle diagram of the mining technology is shown in Figure 1.

3. Theoretical Analysis of Overlying Rock Migration Law

Compared with the traditional caving method to manage the roof, the mining-dressing-backfilling avoids the continuous increase of the overhang area of the working face roof but fills the roadway in time during the mining process of the next roadway after the mining of each roadway is completed. After the goaf is filled with the filling paste, as the filling paste gradually solidifies, the overlying roof of the goaf is effectively supported, which restricts the free movement of the overlying strata. Therefore, compared with caving mining, continuous mining face paste filling can reduce the surface deformation caused by mining and protect the surface buildings and the surface environment.

Taking three-stage mining as an example, in the first-stage mining process of continuous mining face paste filling, the surrounding rock deformation of the filling roadway is very small due to the support of coal pillars during the driving process of the filling roadway. After the backfill roadway is filled, chain pillar changes from a two-dimensional stress state to a three-dimensional stress state, and the stability is enhanced. With the strengthening of the rock support, the movement of the overlying rock gradually stopped, and the cracks in the roof of the filling roadway were not developed during the two processes, and only slight bending deformation occurred, as shown in Figure 2.

After the first stage of continuous mining face paste filling is completed, during the second stage of roadway mining and filling, as the width of the coal pillar gradually decreases, the stress generated by the overlying rock on the coal pillar gradually increases, and the compression deformation of the coal pillar increases gradually. With the subsidence of the overlying strata, the filling body gradually shares the stress of the overlying rock while forming lateral support for the coal pillar, which strengthens the stability of the coal mass. However, the strength and stiffness of the filling body are smaller than those of the coal pillar. Therefore, compared with the one-stage mining and charging process, the migration of the overlying strata increases, when the sinking of the overlying Strata exceeds its maximum deflection. The overlying stratum will produce fissures, and with the increase of the subsidence of the overlying strata, the stress on the backfill and the coal pillar increases gradually. Until the backfill, coal pillars and overlying strata form a new mechanical balance, the overlying strata stop sinking, and Figure 3 shows the migration of overlying rock after the second stage of mining and filling.

After the third stage of continuous mining face paste filling is completed, since the support of the coal pillar to the overlying stratum is lost, the overlying strata will undergo greater subsidence and deformation compared with the second stage. With the gradual solidification and compression of the backfilling body, the stress on the backfilling body gradually increases, and the corresponding reaction force formed by the backfilling body gradually meets the requirements of preventing the overlying rock from sinking, and the overlying rock layer tends to be stable. The degree of fracture development and the amount of subsidence reached a peak. In the third stage, the overburden strata migration is completed as shown in Figure 4.

Through the analysis of the overburden strata migration during the continuous mining face paste filling mining process, it can be seen that during the mining process of mining face paste filling, with the progress of the mining and filling cycle, the filling body gradually replaces the coal pillar to support the overlying strata. In the first and second stages of mining, the coal pillar and the filling body control the overburden subsidence cooperatively, and in the third stage, only the filling body bears the pressure of the overlying stratum. At the same time, it can be seen from the analysis that the overlying strata avoided the generation of caving zones during the continuous mining face paste filling mining process, and only fractured zone and continuous deformation zone appeared.

According to the analysis of the migration of the overlying rock with the paste filling in the continuous mining face, it can be known that with the progress of the mining and filling process, the width of the backfilling body gradually increases. When the coal body of the working face is completely replaced by the backfilling body, the subsidence of the roof of the working face is the largest. Establish

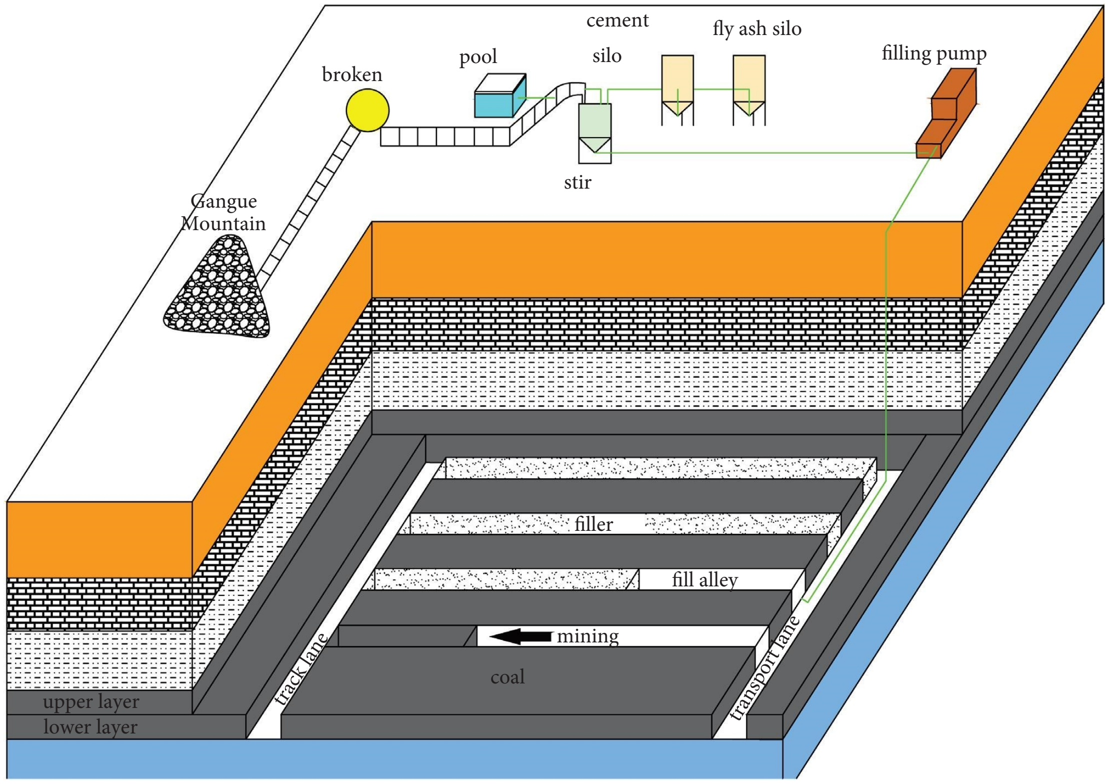


Figure 1: Schematic diagram of mining technology.

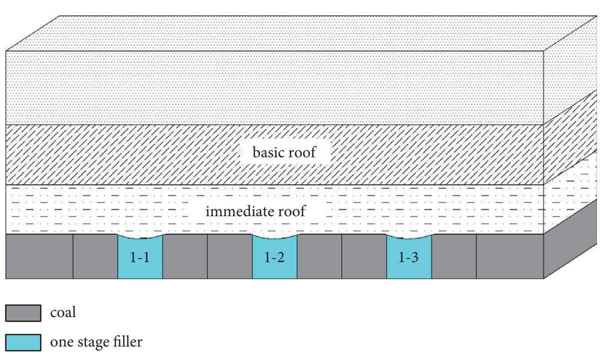


Figure 2: The migration of overlying rock after the first stage of mining and filling is completed.

a mechanical model for the upward and downward continuous mining of thick coal seam with paste filling of upper and lower layers after mining is completed, as shown in Figures 5 and 6.

It can be seen from Figure 5 that when the sublayer filling is mined, the deflection equation of the roof is [30]

$$EI\frac{d^4\omega_1(x)}{dx^4} + k_1\omega_1(x) = q\,(x \le 0),$$
$$EI\frac{d^2\omega_2(x)}{dx^4} + k_3[\omega_2(x) - \mu_1] = q\,(0 \le x \le L), \qquad (1)$$

where k_1 is coal body foundation coefficient, k_3 is combined foundation coefficient of coal and backfilling body under roof in backfill area, $\omega_1(x)$ is the deflection of the upper beam of the coal body after mining and filling of the lower layer, and $\omega_2(x)$ is the deflection of the upper beam of the backfilling body after mining and filling of the lower layer.

Solve equation (1):

$$\omega_1(x) = e^{\alpha_1 x}(G_1\cos\alpha_1 x + G_2\sin\alpha_1 x) + \frac{q}{k_1}\,(x \le 0),$$
$$\omega_2(x) = e^{-\alpha_2 x}(H_1\cos\alpha_2 x + H_2\sin\alpha_2 x) + \frac{q}{k_3} + \mu_1\,(0 \le x \le L). \qquad (2)$$

According to boundary conditions and continuity conditions, G_1, G_2, F_1, and F_2 are obtained as [30]

$$G_1 = \frac{\alpha_2^2}{\alpha_1^2}\left(\frac{q}{k_3} + \mu_1\right),$$
$$G_1 = \frac{\alpha_1 - \alpha_2}{\alpha_1 + \alpha_2}\left(\frac{q}{k_3} + \mu_1\right),$$
$$F_1 = -\left(\frac{q}{k_3} + \mu_1\right),$$
$$F_2 = \frac{\alpha_1 - \alpha_2}{\alpha_1 + \alpha_2}\left(\frac{q}{k_3} + \mu_1\right). \qquad (3)$$

Then, the deflection function of the roof rock beam in the backfill area during the lower layer mining is

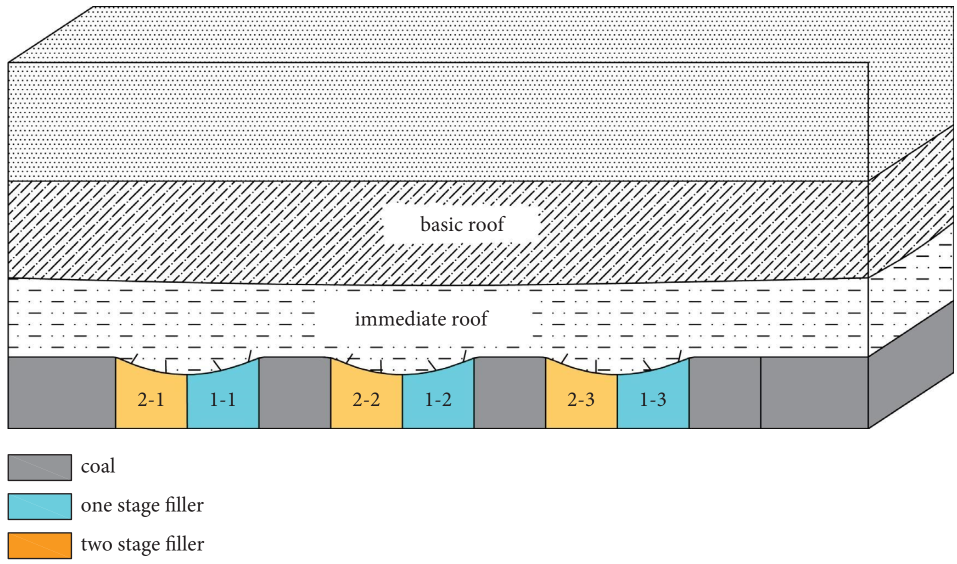


Figure 3: The migration of overlying rock after the second stage of mining and filling is completed.

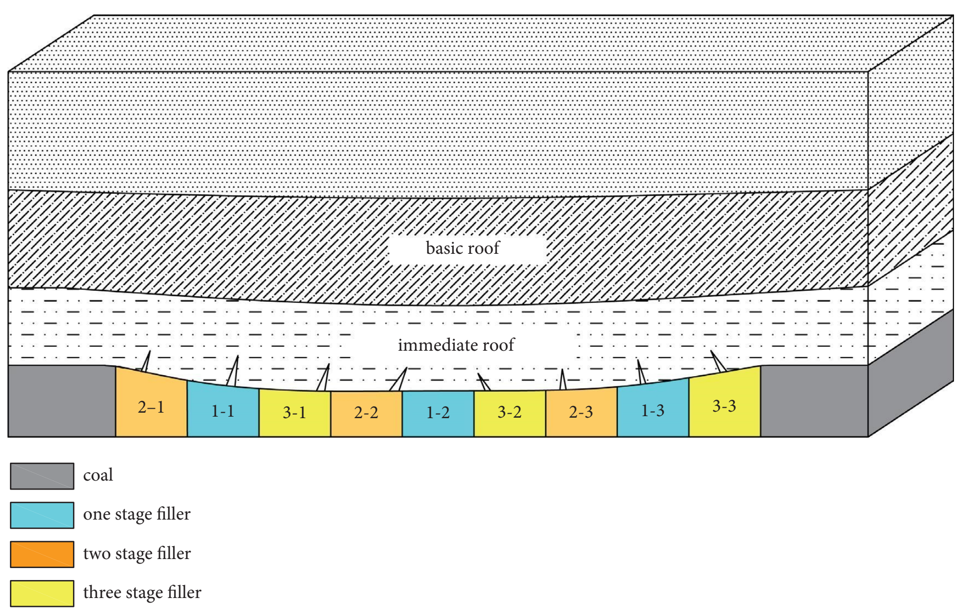


Figure 4: Overburden migration map after mining and filling in the third stage.

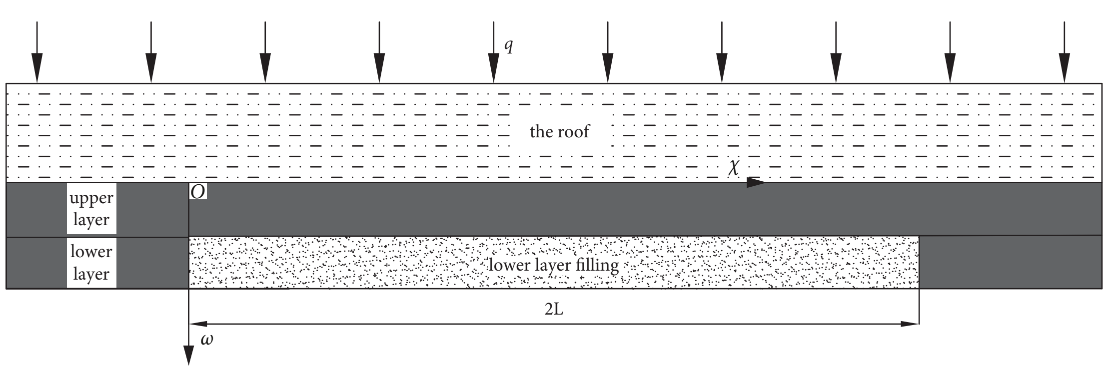


Figure 5: Overlying rock migration model when the lower layer filling is completed.

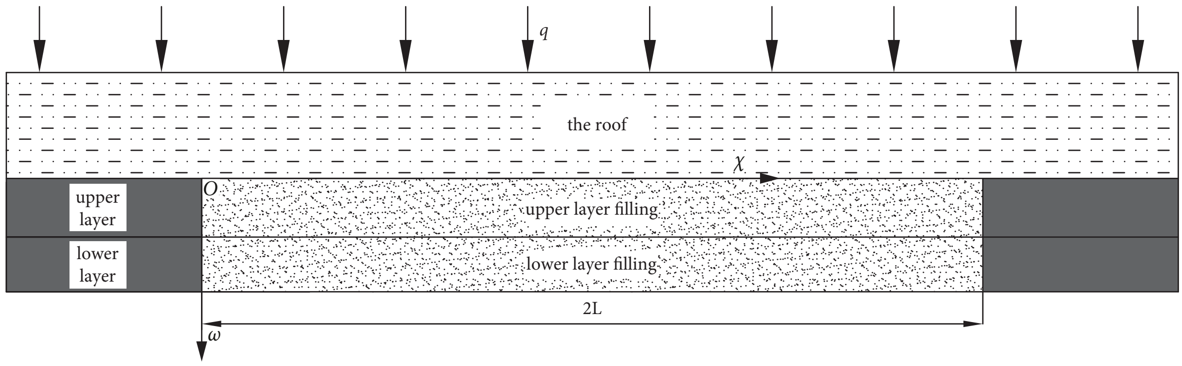


Figure 6: Overlying rock migration model when the upper layered filling is completed.

$$\omega_2(x) = e^{-a_2 x}\left(\frac{\alpha_1-\alpha_2}{\alpha_1+\alpha_2}\sin\alpha_2 x - \cos\alpha_2 x\right)\left(\frac{q}{k_3}+\mu_1\right) + \left(\frac{q}{k_3}+\mu_1\right)(0\le x\le L). \tag{4}$$

When the upper layer is mined, the roof filling area and the coal body area have sunk $\omega_1(x)$ and $\omega_2(x)$, respectively, during the lower layer mining; therefore, the roof deflection equation should be

$$EI\frac{d^4\omega_3(x)}{dx^4} + k_2\left[\omega_3(x)-\omega_1(x)\right] = q(x\le 0),$$
$$EI\frac{d^4\omega_3(x)}{dx^4} + k_2\left[\omega_4(x)-\omega_2(x)-\mu_1\right] = q(0\le x\le L), \tag{5}$$

where k_2 is coal body foundation coefficient, ω_3 is the deflection of the upper beam of the coal body after the upper layer is mined and filled, and ω_4 is the deflection of the upper beam of the backfilling body after the upper layer is mined and filled.

The deflection equation for layered mining can be solved as

$$\omega_4 = e^{-a_3 x}\left(\frac{\alpha_3-\alpha_1}{\alpha_1+\alpha_3}\sin\,\alpha_3 x - \cos\,\alpha_3 x\right)\left(\frac{q}{k_2}+\mu_2\right) + \frac{q}{k_2}+\omega_2(x)+\mu_2(0\le x\le L). \tag{6}$$

In order to study the influence of different factors on the roof migration in the backfill area, the values of each parameter in the *formula* were clarified based on the mining geological conditions of the coal mine. Direct top elastic modulus $E = 22.00$ GPa; moment of inertia $I = 2.39$; filler elastic modulus $E_c = 1.00$ GPa; layer thickness up and down $h1 = h2 = 3.35$ m; coal elastic modulus $E_m = 1.20$ GPa; and coal thickness is 6.70 m. The coal seam is buried at a depth of 223 m. The subsidence amount of the roof before filling is 0.1 m.

Substitute the above parameters into the formula and use the mathematical software MATLAB to obtain the roof subsidence curve when the upper and lower layers are mined with different influencing parameters, as shown in Figures 7 and 8.

After the upper and lower layers are collected and charged, when the elastic modulus of the infill increases from 0.20 GPa to 0.40 GPa, the maximum subsidence of the roof decreases from 650 mm to 430 mm, and when the elastic modulus of the infill increases from 0.80 GPa to 1.00 GPa, the maximum subsidence of the roof decreases from 210 mm to 170 mm; with the increase of the elastic modulus of the filling body, the subsidence of the roof gradually decreases, and the decrease shows a decreasing trend. Continuing to increase the elastic modulus of the filling body will increase the filling cost if the roof control effect cannot be effectively increased, so it is more appropriate to control the elastic modulus of the filling body at about 0.80 GPa.

4. Numerical Simulation Research

Combined with the actual mining geological conditions of coal mines, the working face is a near-horizontal coal seam, so the model does not consider the influence of dip angle. Set the model size length $(X) \times$ width $(Y) \times$ height (Z) to 420 m × 480 m × 253 m. The X direction is the inclination direction of the working face, and the Y direction is the direction of the working face. The inclination length of the working face is 320 m, the design advancing distance is 360 m, and 50 m is left on both sides of the inclination. 60 m protective coal pillars were left on both sides of the strike to reduce the influence of boundary effects on the simulation results. All regions in the mesh are defined as the Mohr–Coulomb elastoplastic model. The model is established as shown in Figure 9.

By testing the rock samples excavated underground, it was found that the structural planes of the top and bottom layers of the coal seam were not developed, so the mechanical parameters of the rock blocks were measured by the indoor rock block test method. To ensure the reliability of

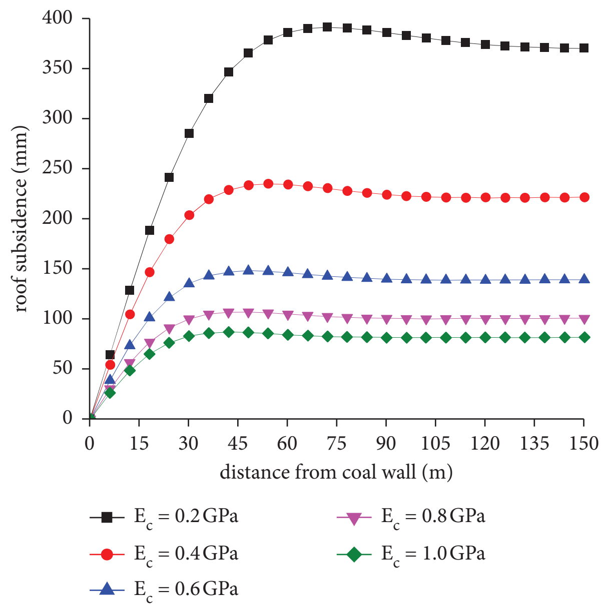


Figure 7: Roof subsidence curve of layered mining area under the influence of elastic modulus of backfill.

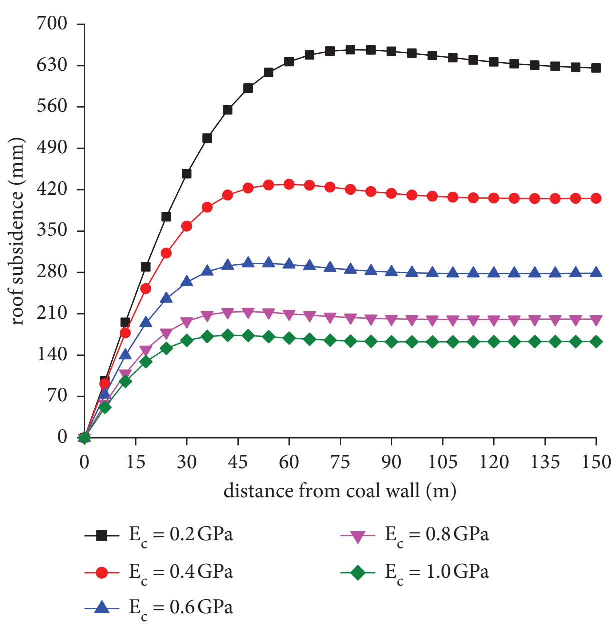


Figure 8: The influence of the elastic modulus of the backfilling body on the subsidence curve of the roof in the upper layered mining area.

the data, it is necessary to collect multiple sets of samples and conduct a large number of tests. After data analysis, the final results are used to approximate the mechanical parameters of the rock mass, as shown in Table 1. These parameters are used in numerical simulations to simulate the extent of surface subsidence.

It can be seen from Figures 10 and 11 that after the paste filling of the upper layered continuous mining face of the thick coal seam is completed, when the elastic modulus of the backfill is 0.20 GPa, 0.40 GPa, 0.60 GPa, 0.80 GPa, and 1.00 GPa, the maximum vertical displacement of the overlying rock is 735 mm, 465 mm, 335 mm, 224 mm, and 188 mm, respectively. From the above data analysis, it can be seen that when the elastic modulus of the backfill increases from 0.20 GPa to 0.40 GPa, the maximum vertical displacement of the overlying rock layer decreases by 270 mm, and when it increases from 0.40 GPa to 0.60 GPa, the maximum vertical displacement of the overlying rock layer decreases. When the elastic modulus of the backfill increases from 0.80 GPa to 1.00 GPa, the maximum vertical displacement reduction of the overlying rock is only 36 mm. It can be seen that under certain other conditions, with the increase of the elastic modulus of the backfilling body, due to the increase of the stress required for the backfilling body to compress, the limiting effect on the migration of the overlying rock layer is gradually strengthened, but this effect increases with the elasticity of the backfilling body. The modulus increases and tends to a certain value.

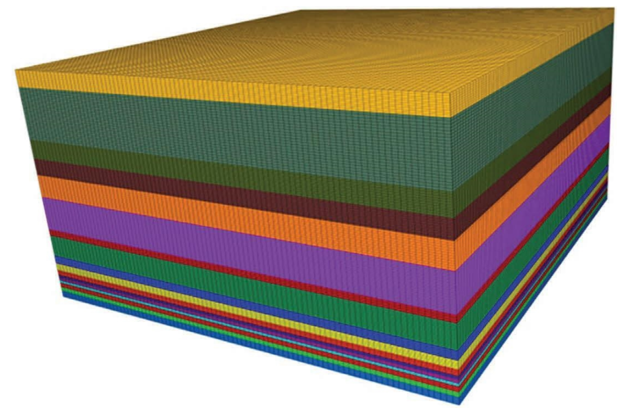


Figure 9: Numerical calculation model.

It can be seen from Figure 12 that with the increase of the elastic modulus of the backfill, the support pressure of the backfill gradually increases, and the layer-by-layer pressure of the coal pillars on both sides gradually decreases. When the elastic modulus of the backfill is 0.20 GPa, the peak vertical stress of the backfill is about 2.70 MPa, and the peak stress of the boundary coal pillar is 14.80 MPa; when the elastic modulus of the backfill is 0.40 GPa, the peak stress of the backfill is about 4.1 MPa. The peak stress of the coal pillars on both sides is 13.01 MPa; when the elastic modulus of the backfill is 0.60 GPa, the peak stress of the backfill is about 5.30 MPa, and the peak stress of the coal pillars on both sides is 12.30 MPa; when the elastic modulus of the backfill is 0.80 GPa, the peak stress of the backfill is about 5.8 MPa, and the peak stress of the coal pillars on both sides is 11.40 MPa; when the elastic modulus of the backfill is 1.00 GPa, the peak stress of the backfill and the peak stress of the coal pillars on both sides are basically the same as those of 0.80 GPa, but the peak stress area of the filling increases. To sum up, since the elastic modulus of the coal body is larger than that of the backfilling body, the deformation of the backfilling body during the mining and filling process of the working face is larger than that of the coal body, so that the stress of the overlying stratum is transferred to the coal bodies on both sides, and with the increase of elastic

Table 1: Mechanical parameters of coal and rock mass.

No.	Lithology	Thickness (m)	Density (kg/m^3)	Young's modulus (GPa)	Poisson's ratio	Internal friction angle (°)	Cohesion (MPa)	Tensile strength (MPa)
1	Topsoil	17.5	1210	0.55	0.44	32.3	0.07	0.15
2	Siltstone	53.5	2570	17.0	0.22	36.5	3.9	2.9
3	Coarse sandstone	20.4	2480	21.5	0.23	32.9	6.8	5.1
4	Mudstone	17.8	2700	18.0	0.21	33.2	6.9	3.8
5	Fine sandstone	24.8	2720	21.0	0.22	38.2	5.6	3.5
6	Siltstone	36.8	2690	18.5	0.22	33.5	6.9	5.2
7	Fine sandstone	9.2	2690	21.0	0.20	39.4	5.6	5.1
8	Medium sandstone	23.7	2170	25.0	0.26	33.0	3.6	3.4
9	Siltstone	14.1	2690	18.5	0.22	34.5	6.3	3.2
10	Mudstone	8.0	2690	19.0	0.20	33.2	6.8	3.8
11	Medium sandstone	4.2	2690	25.0	0.25	34.0	5.8	2.9
12	Fine sandstone	3.0	2730	22.0	0.21	32.5	5.5	4.5
13	Coal	6.7	1200	1.2	0.29	33.0	2.1	1.3
14	Fine sandstone	2.9	2730	22.0	0.26	30.9	7.5	3.4
15	Medium sandstone	5.1	2730	23.0	0.25	31.6	8.0	3.5
16	Mudstone	4.6	2680	21.0	0.23	33.0	7.7	3.0
17	Argillaceous sandstone	7.4	2720	18.0	0.21	33.4	6.0	3.2

modulus of the backfilling body, the deformation of the backfilling body and the coal body gradually decrease, the gravity distribution in the overlying stratum is gradually uniform, and the stress of the overlying rock gradually transfers to the backfilling body.

It can be seen from Figure 13 that when the elastic modulus of the filling increases from 0.20 GPa to 0.40 GPa, the failure height and extent of the plastic zone decrease very little. When the elastic modulus of the backfill is 0.20 GPa, the height of the plastic zone of the model is 71 m, and the plastic zone develops to the lower part of the No. 6 siltstone layer of the overlying layer. When the elastic modulus of the backfill increases to 0.40 GPa, the height of the plastic zone of the model decreases by 12 m, and the plastic zone reaches the middle and upper part of the No. 7 fine sandstone layer of the overlying stratum. This is because the backfill cannot face upward due to the small elastic modulus of the backfill. The overlying stratum forms an effective support, resulting in greater tensile, shearing, and other damage to the overlying strata. When the elastic modulus of the filling increases from 0.40 GPa to 0.8 GPa, the backfill begins to form a certain supporting effect on the overlying rock. With the increase of the elastic modulus of the filling body, the supporting effect is gradually strengthened, and the height and range of the plastic zone of the model decrease rapidly. When the modulus of the backfill is 0.60 GPa, the height of the model plastic zone is reduced to 40 m, and the reduction in the height of the plastic zone from the plastic zone to the middle of the sandstone layer in overlying layer No. 8 is about the same as the reduction in the elastic modulus from 0.20 GPa to 0.40 GPa. When the elastic modulus of the backfill increases from 0.60 GPa to 0.80 GPa, the height of the model plastic zone drops to 18 m, and the plastic zone develops to the bottom of the No. 9 siltstone layer of the overlying stratum. The height of the plastic zone in the two processes was reduced by 75% of the whole process. When the elastic modulus of the filling body increases from 0.80 GPa to 1.00 GPa, the plastic zone only appears in part of the filling body and the direct roof. Although the supporting effect of the filling body is further strengthened, the plastic zone of the model is further reduced, but because the plastic zone is at 0.8 GPa, the height is already very small, so the height reduction is limited. It can be seen from Figure 14 that with the increase of the elastic modulus of the backfilling body, the surface subsidence and the surface tilt deformation corresponding to the paste backfill mining of the upward layered continuous mining face of the thick coal seam are obviously reduced, and the corresponding elastic modulus of the backfilling body is different. The maximum subsidence value of the ground surface is 527.25 mm, 327.46 mm, 217.55 mm, 163.99 mm, and 142.56 mm, and the maximum slope deformation value of the ground surface corresponding to the elastic modulus of different filling bodies is 5.05 mm/m, 3.12 mm/m, 2.28 mm/m, 1.47 mm/m, and 1.25 mm/m; it can be seen that the lower the elastic modulus of the backfill, the more severe the surface tilting deformation after the paste backfill mining of the layered continuous mining face on the thick coal seam.

According to the "Coal mining under buildings and railroads and water-bodies" coal mining code, it can be known that when the brick-concrete structure on the ground is at the level I damage level, the elastic modulus of the backfill at this time is not less than 0.6 GPa. Combined with the control of overlying rock with different filling rates and the influence of different elastic modulus of filling body on the roof in the theoretical part, when the elastic modulus of filling body is 0.8 GPa, it can better control the subsidence of overlying rock and ensure the safety of surface buildings.

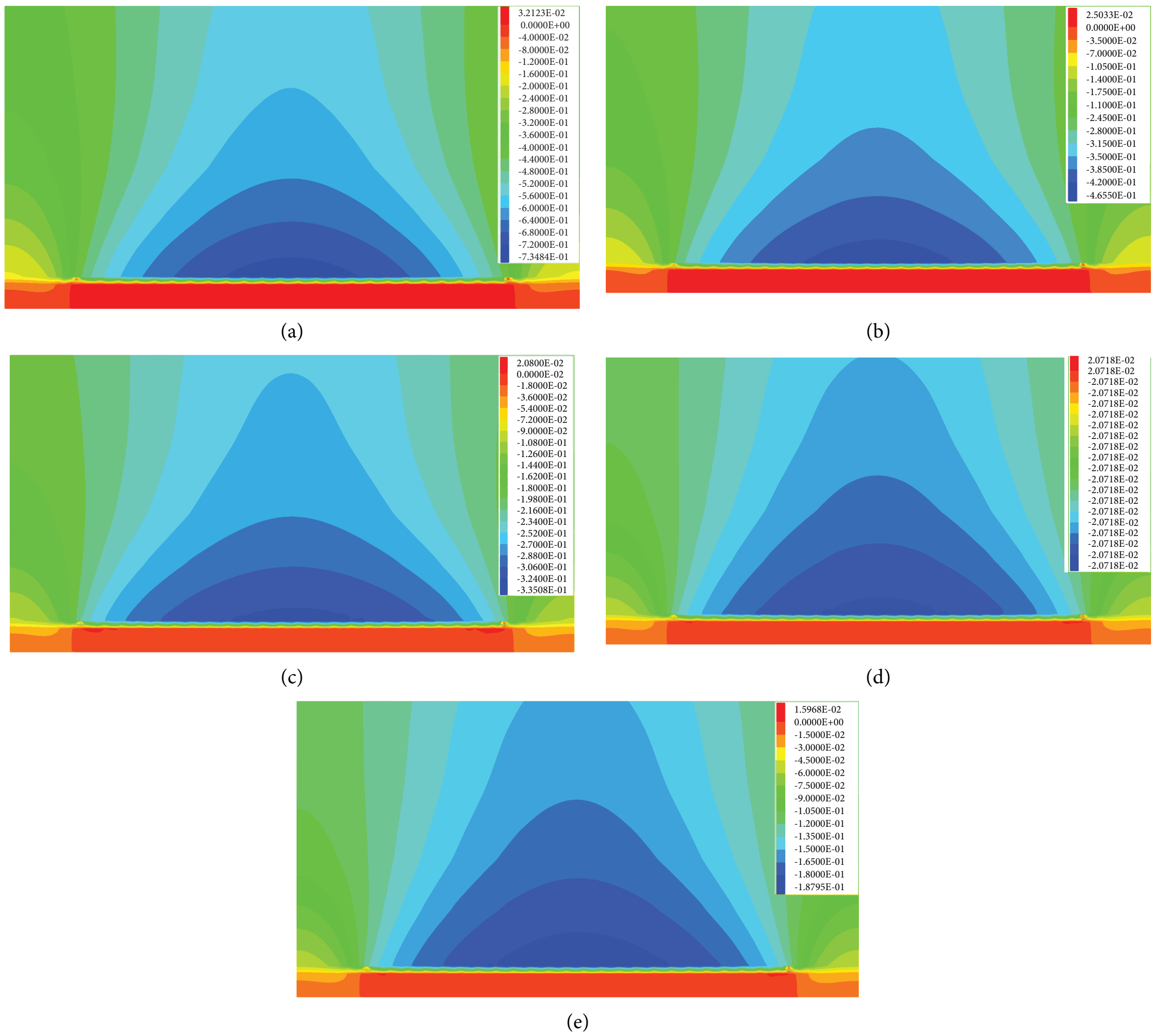


Figure 10: Cloud map of vertical displacement of overlying rock with different elastic moduli of backfill. (a) The elastic modulus of the filling body is 0.2 GPa. (b) The elastic modulus of the filling body is 0.4 GPa. (c) The elastic modulus of the filling body is 0.6 GPa. (d) The elastic modulus of the filling body is 0.8 GPa. (e) The elastic modulus of the filling body is 1.0 GPa.

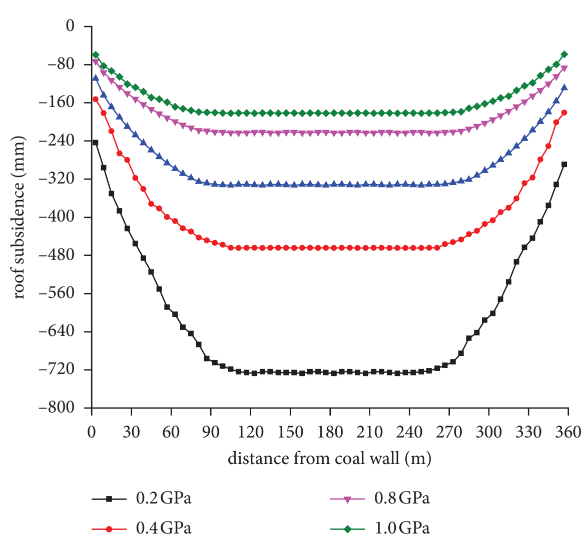


Figure 11: Roof subsidence curve of different filling bodies' elastic modulus.

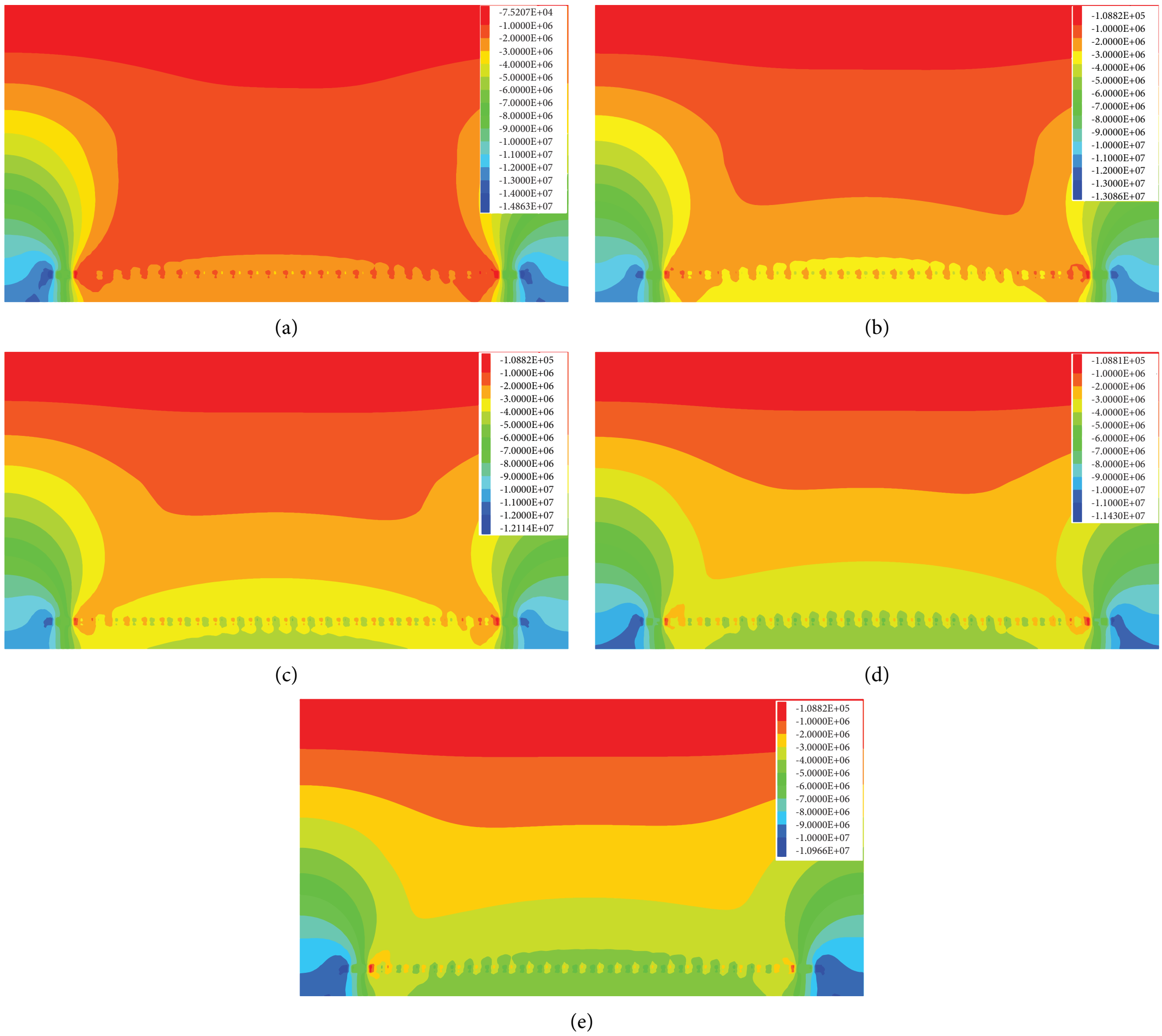


Figure 12: Vertical stress cloud diagram of overlying rock with different elastic moduli of backfill. (a) The elastic modulus of the filling body is 0.2 GPa. (b) The elastic modulus of the filling body is 0.4 GPa. (c) The elastic modulus of the filling body is 0.6 GPa. (d) The elastic modulus of the filling body is 0.8 GPa. (e) The elastic modulus of the filling body is 1.0 GPa.

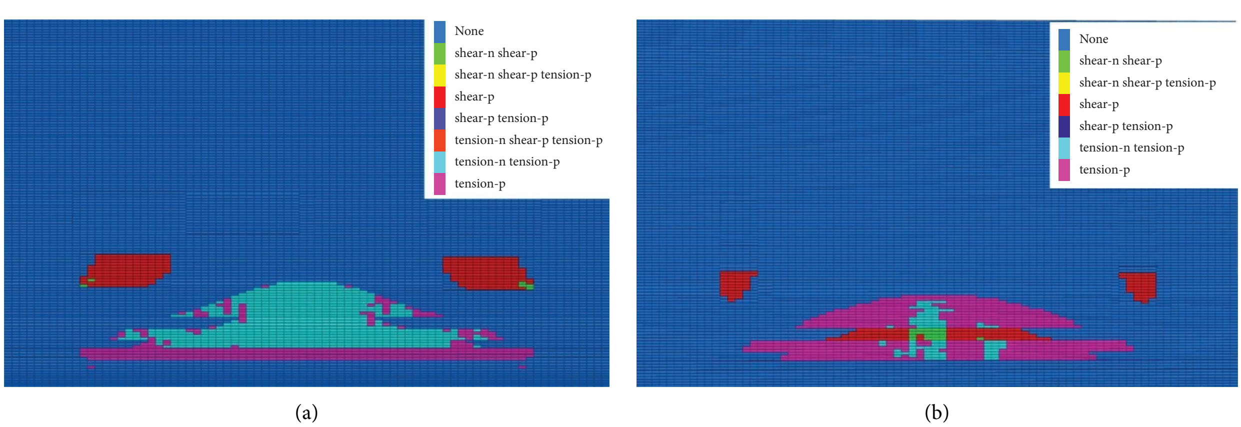
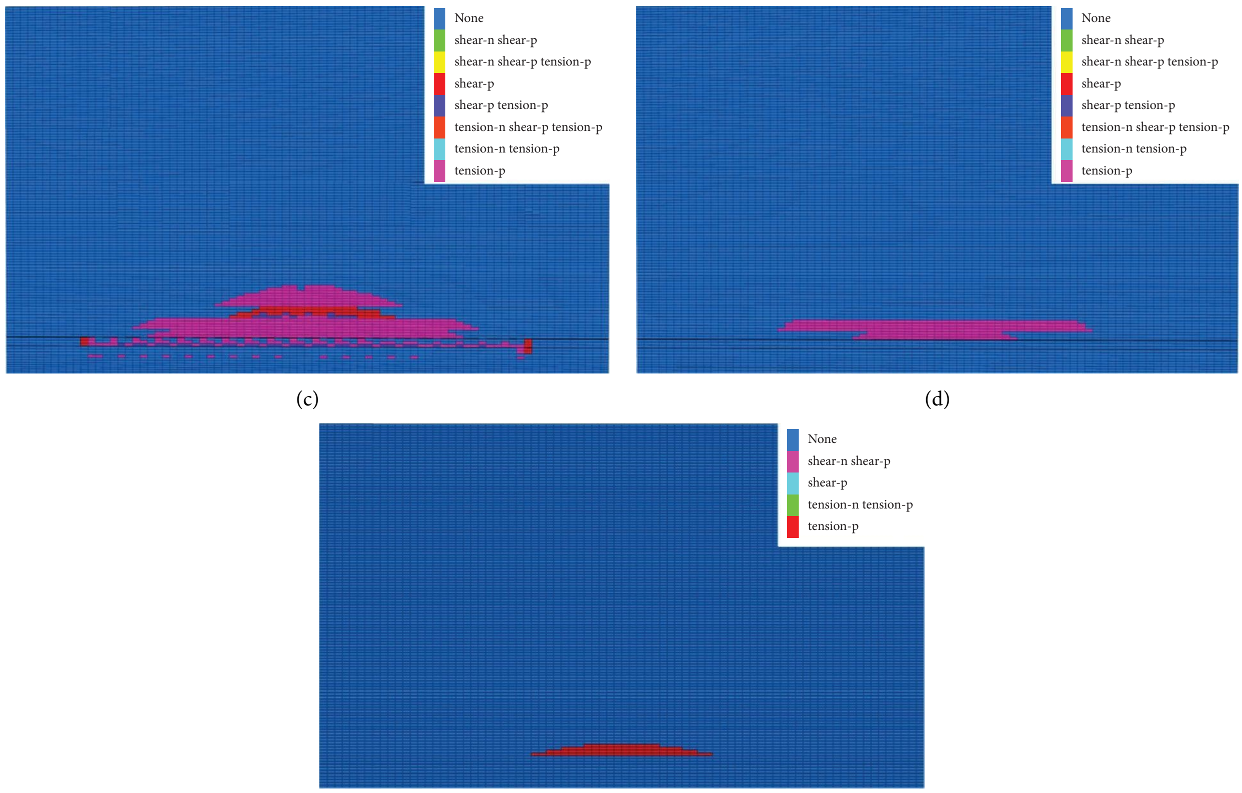


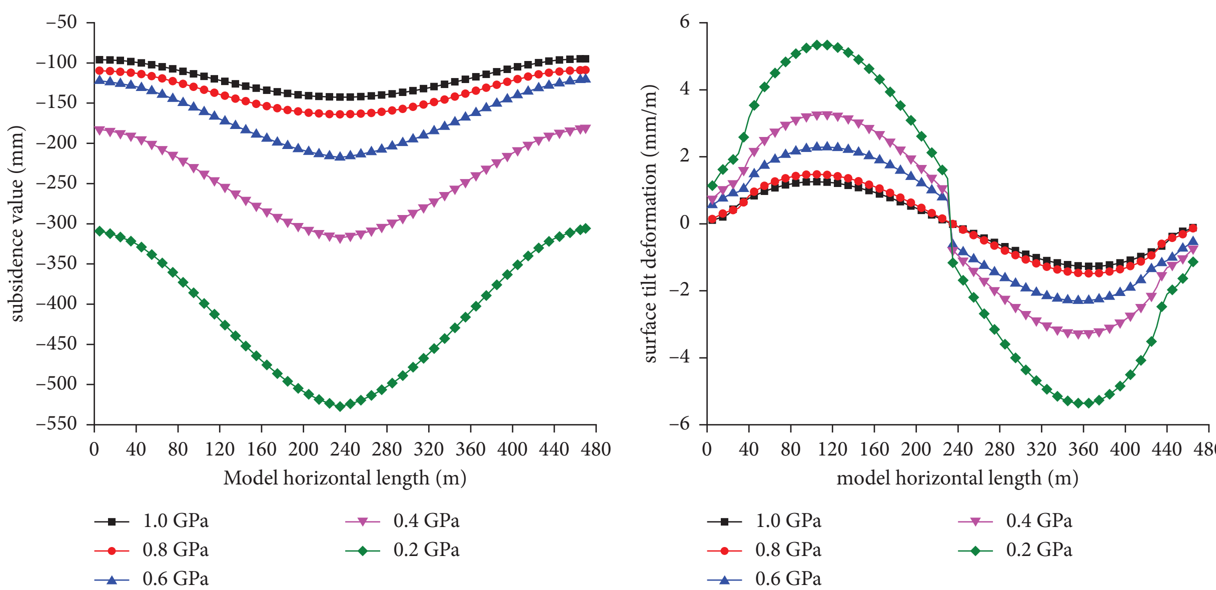
Figure 13: Continued.



(c) (d)

(e)

Figure 13: Plot of the plastic zone of elastic modulus of different filling bodies. (a) The elastic modulus of the filling body is 0.2 GPa. (b) The elastic modulus of the filling body is 0.4 GPa. (c) The elastic modulus of the filling body is 0.6 GPa. (d) The elastic modulus of the filling body is 0.8 GPa. (e) The elastic modulus of the filling body is 1.0 GPa.



(a) (b)

Figure 14: Surface deformation curve of mining with different backfill elastic moduli. (a) Surface subsidence curve. (b) Surface tilt deformation curve.

5. Conclusion

In this paper, taking coal mining under a coal mine building as the engineering background, through theoretical analysis, numerical simulation, and other research methods, the migration law of overlying rock in the upward layered continuous mining face paste filling mining in thick coal seam is studied and analyzed. It simulates and analyzes the effect of the elastic modulus of the backfilling body on the migration of overlying rock and surface deformation.

(1) The elastic modulus of different filling bodies has obvious influence on the subsidence of the overlying strata. With the continuous increase of the elastic modulus of the backfill, the subsidence of the overlying stratum gradually decreases, and the decrease shows a trend of first increasing and then decreasing.

(2) The range and height of the infill are gradually reduced, and the complexity of the failure form is gradually reduced; the elastic modulus of the filling body to ensure the safety of the surface building is determined to be 0.8 GPa.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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