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Research Article

Study on Failure Characteristics and Reasonable Mining Parameters of Upward Mining of Integrated Coal Mine

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In order to avoid the problem of repeated repair of roadways in the upper mining area of upward mining in the integrated mine, taking the roadways in the 302 mining area of Shancheng Coal Mine as the research object, the failure characteristics of overlying strata and the evolution characteristics of roadway plastic zone in the mining process of underlying coal seam were studied by combining theoretical analysis, numerical simulation, and engineering measurement. The influence law of underlying coal seam mining on the integrity of 3# coal seam and the stability of roadways in the 302 mining area was revealed, and the repair opportunity of roadways in the upper coal seam and the reasonable position of open-off cut in the lower coal seam working face were determined. The research shows that due to the influence of the mining of the working face in the underlying coal seam, the plastic failure of the overlying strata is serious during the upward mining of Shancheng Coal Mine, but there is no step dislocation, but the overall subsidence is presented. The plastic zone range of roadway in 302 mining area first increases and then tends to be stable with the mining of 97308 working face in underlying coal seam, and the roadway repair should be carried out after 280 m advance of 97308 working face. Based on the coordination between the influence of the cutting position of the underlying coal seam on the variation characteristics of the plastic zone of the upper roadway and the saving of coal resources, it is determined that the cutting position of the underlying 153308 working face is advanced to 340 m. The field engineering application shows that the deformation of roadway surrounding rock meets the production requirements by implementing the above mining parameters, and the rerepair of roadway surrounding rock deformation in 302 mining area of 3# coal seam is avoided.

1. Introduction

In recent years, in order to improve the recovery rate of coal resources, China has actively implemented relevant policies such as coal resource integration and mine merger and reorganization, which has led to the ascending mining of some integrated mines [1–4], such as Jincheng Coal Mine in Shanxi Province. Ascending mining is a common method for mining two or more coal seams with a certain spacing, especially in hard coal seam, coal seam with large water content, coal and gas outburst coal seam, and other special conditions, which often has strong advantages [5–8]. However, if the mining parameter design is unreasonable, the mining of the lower coal seam will cause the overall structure of the overlying strata to change, affecting the integrity of the upper coal seam and the stability of the roadway [9–15], resulting in large deformation of the surrounding rock of the upper coal seam roadway and multiple repairs [16–18]. Therefore, it is of great significance to study the failure characteristics of the upper coal seam in the mining process of the underlying coal seam and the influence law on the deformation of the surrounding rock of the roadway in the upper mining area, and to clarify the influence degree of the mining activities of the underlying coal seam on the upper coal seam, so as to determine the reasonable mining parameters of the lower coal seam, and to realize the safe production of the mine.

Many scholars at home and abroad have done a lot of research on the failure characteristics of ascending mining of coal seam and its influence on upper roadway. Guan [19] used a borehole water injection technology to conduct field measurement on the development of overlying strata, revealing that ascending mining can be safely carried out when the upper coal seam is located in the bending subsidence zone of the lower coal seam. Based on the "composite cantilever beam-hinged rock beam" structure, Sun et al. [20] deduced the discriminant formula of the roof balance structure state and proposed that the upper coal seam can be mined upward when it is above the "equilibrium structure formation layer." Based on the results of numerical simulation test, Yuan and He [21] put forward the step error momentum of the upper coal seam as an index to determine whether it can be safely ascending mining. When the step error momentum is greater than the thickness of the upper coal seam, the upper coal seam has good continuity and can be safely ascending mining. Qiao [22] analyzed the influence of coal seam spacing and lower coal seam mining height on the feasibility of ascending mining and clarified that large spacing and small mining height conditions were conducive to ascending mining of coal seams. Qian et al. [23] put forward a method of sectional freezing roof caving in view of the difficult problem of water-accumulating and emptying mining in cutter-pillar residual mining area. Shao et al. [24] monitored the caving and migration law of upper strata through similar simulation test, which showed that the integrity of upper coal seam was better when it was above fracture zone.

However, most of the existing studies focus on whether the ascending mining of coal seam is feasible, less involving the influence of rock failure on the upper coal seam roadway and the reasonable determination of mining parameters to reduce its influence. Therefore, this paper takes the roadway in 302 mining area of 3# coal seam in Shancheng Coal Mine as the engineering background, and adopts the method of combining theoretical analysis and numerical simulation to study the failure characteristics of overlying strata and the influence law on the deformation of surrounding rock of roadway in 302 mining area caused by the mining of working face in underlying 9# and 15# coal seam, and determines the rework opportunity of roadway in 302 mining area and the reasonable cut position of working face in lower coal seam, so as to avoid the problem of repeated repair of roadway and provide reference for the ascending mining of similar coal mines.

2. Engineering Background

Shancheng Coal Mine is located in the area of Goudi Village, Beiliu Town, Yangcheng County, Shanxi Province. It is integrated by the original Shancheng wellhead and the ditch bottom wellhead, and the production capacity is 600,000 t/a. At present, the main coal seam is 3# coal seam of Shanxi Formation, the coal seam thickness is 5.43~7.20 m, the average thickness is 6.3 m, the roof is mudstone, and the 9# and 15# coal seams of Taiyuan Formation are matched coal seams. The coal seam thickness is 1.20~1.65 m and 1.90~2.70 m, and the average thickness is 1.3 m and 2.66 m, respectively. The roof is fine sandstone and limestone. Among them, the 9# coal seam upward distance 3# coal seam is 53.5~56.7 m and 15# coal seam upward distance 3# coal seam is 85.2~89.2 m, the mine comprehensive histogram is shown in Figure 1. The 302 mining area of 3# coal seam is located in the south of the mine field, and the mining area is about 3.34 km^2. There are three roadways with belt uphill, track uphill, and return air uphill. Affected by the mining of 97307 working face, the roadway in 302 mining area has large deformation, mainly located in the 50~265 m section of the south side of the substation in the mining area. The spatial relationship between the roadway in the mining area and the underlying coal seam and the position of the roadway deformation section are shown in Figure 2. The roadway deformation is characterized by roof subsidence, two sides moving inward and the roadway section shrinkage, as shown in Figure 3. Therefore, in order to avoid the continuous deformation of roadway in 302 mining area during the subsequent mining of 97308 working face and 15 coal seam working face, it is necessary to clarify the repair time of roadway in 302 mining area and the opening and cutting position of lower coal seam working face.

3. Failure Characteristics and Mining Feasibility of Upper Coal Seam

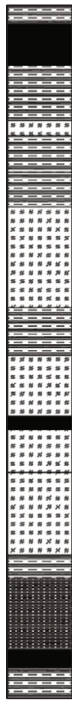
Studies have shown that the feasibility of upward mining depends on the degree of damage to the overall structure of the upper coal seam. When the upper coal seam is located in the bending subsidence zone of the underlying coal seam, its continuity and integrity are good, and the upward mining can be safe [24]. Therefore, according to the coal seam conditions of Shancheng Coal Mine, the feasibility of upward mining of 3# coal seam is judged by mining impact multiplier method, "three zones" discrimination method and surrounding rock equilibrium method, and FLAC3D modeling is used to analyze the failure characteristics of the overlying strata and the deformation of 3# coal seam after mining.

3.1. Theoretical Analysis

3.1.1. Mining Impact Multiplier Method. The mining influence multiple method mainly determines the feasibility of upward mining by influencing the relationship between coal seam spacing and lower coal seam mining height. Under the mining conditions of multiple lower coal seams, the calculation formula of mining influence multiple K is

$$K = \frac{1}{1/K_1 + 1/K_2 + \cdots + 1/K_{n-1} + 1/K_n}. \tag{1}$$

In the formula, $K_1 = h_1/m_1$, $K_2 = h_2/m_2$,……, $K_n = h_n/m_n$, and h_1, h_2,……, h_n are, respectively, the 1st, 2nd… spacing between n layer and mining layer, m; m_1, m_2,……, m_n are, respectively, the 1st, 2nd... n seam thickness, m.



Lithologic characters	Thickness (m)	Average thickness (m)
Mudstone	2.63 ~ 3.02	2.8
3 # coal seam	6.25 ~ 6.38	6.3
Mudstone	8.05 ~ 8.24	8.2
Post office box stone	2.63 ~ 2.80	2.7
Mudstone	5.63 ~ 6.02	5.8
Limestone	4.43 ~ 4.78	4.6
Siltstone	15.32 ~ 16.02	15.62
Mudstone	8.44 ~ 8.80	8.6
Post office box stone	9.03 ~ 9.47	9.2
9 # coal seam	1.02 ~ 1.54	1.3
Post office box stone	6.63 ~ 6.96	6.79
Medium grained sandstone	10.63 ~ 10.82	10.76
Mudstone	3.43 ~ 3.82	3.66
Limestone	9.95 ~ 10.34	10.17
15 # coal seam	2.53 ~ 2.78	2.66
Mudstone	4.03 ~ 4.46	4.24

Figure 1: Comprehensive histogram of mine.

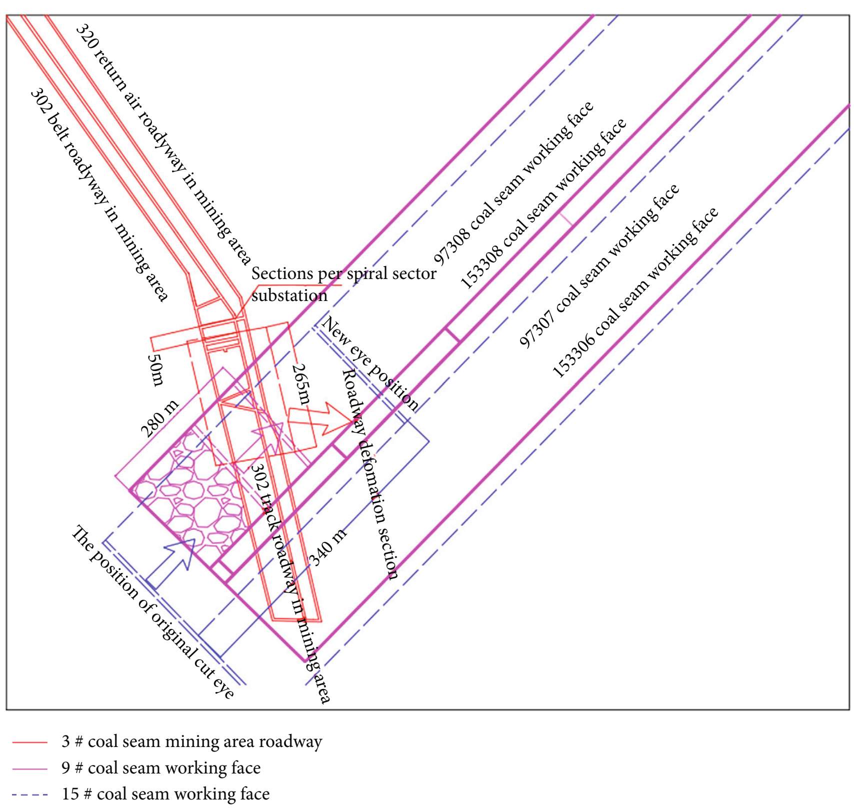


Figure 2: Spatial relationship diagram of roadway and underlying coal seam in 302 mining area.

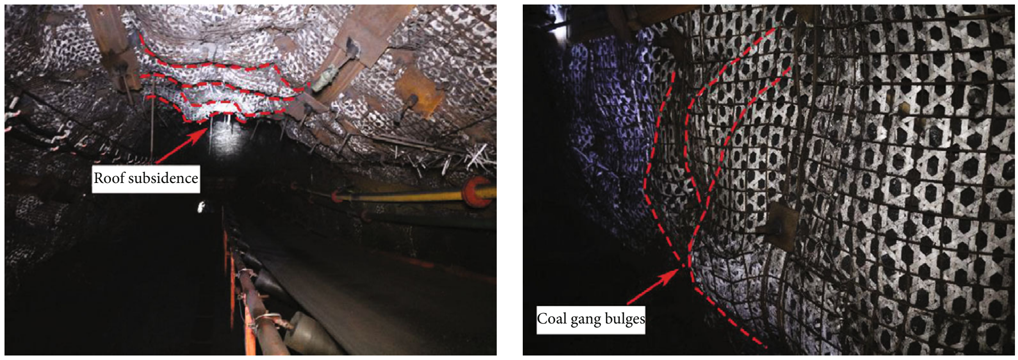


FIGURE 3: Deformation diagram of roadway affected by mining. (a) roof subsidence and (b) coal gang bulges.

A large number of upward mining studies in China show that when the mining influence multiple $K > 7.5$, the overall structure of the upper coal seam is less affected by the mining of the underlying coal seam [25]. The maximum thickness of 9# coal seam in Shancheng Coal Mine is 1.54 m, the minimum distance from 3# coal seam is 53.5 m, the maximum thickness of 15# coal seam is 2.78 m, and the minimum distance from 3# coal seam is 85.2 m. Formula (1) calculates that K is 16.00, greater than 7.5.

3.1.2. "Three Zones" Discrimination Method. After the mining of underlying coal seam, the strata above goaf move and deform, forming caving zone, fracture zone, and bending subsidence zone. A large number of theoretical studies have shown that when the spacing between the upper and lower coal seams is less than or equal to the height of the caving zone of the lower coal seam, the structure of the upper coal seam will be seriously damaged and the upward mining cannot be carried out. When the distance between the upper and lower coal seams is less than or equal to the height of the fracture zone, the upper coal seam structure only has moderate damage. After taking certain safety measures, the upward mining can be carried out normally. When the distance between the upper coal seam and the lower coal seam is greater than the height of the fracture zone of the lower coal seam, the upper coal seam only moves overall and the structure is not destroyed, and the upward mining can be carried out normally. Therefore, it is necessary to clarify the height of the caving zone and fracture zone formed after the mining of the lower coal seam.

The uniaxial compressive strength of roof strata in 9# and 15# coal seams of Shancheng Coal Mine is 23.2~34.8 MPa, which is medium hard rock. The height of caving zone and fracture zone can be calculated by formula (2) and (3), respectively [25].

$$H_{\mathrm{m}} = \frac{100\sum M}{4.7\sum M + 19} \pm 2.2, \tag{2}$$

$$H_{l} = \frac{100\sum M}{1.6\sum M + 3.6} \pm 5.6. \tag{3}$$

In the formula, $\sum M$ is the cumulative thickness, m; H_l is the height of fracture zone, m; and H_m is the height of caving zone, m.

The maximum thicknesses of 9# and 15# coal seams in Shancheng Coal Mine are 1.54 m and 2.78 m, respectively. Substituting them into formulas (2) and (3), the maximum heights of caving zone are 7.58 m and 15.72 m, respectively, and the maximum heights of fracture zone are 29.25 m and 35.68 m, respectively. The minimum distance between 9# coal seam and 3# coal seam is 53.5 m, and the minimum distance between 15# coal seam and 3# coal seam is 85.2 m. It can be seen that 3# coal seam will be located above the fracture zone of 9# and 15# coal seam.

3.1.3. Surrounding Rock Equilibrium Method. According to the balance theory of surrounding rock, the balanced rock stratum (key stratum) can act as the skeleton of the overlying strata to maintain the balance and stability of the rock stratum. Therefore, when the upper coal seam is located above the balanced rock stratum of the lower coal seam, it can be mined upward [26]. Among them, the equilibrium height of surrounding rock is the height from the lower coal seam roof to the equilibrium rock roof, which is calculated by

$$Hb = \frac{M}{K - 1} + h. \tag{4}$$

In the formula, H_b is the balance height for surrounding rock, m; M is the mining height for lower coal seam, m; K is the rock bulking coefficient; and h is the balance rock height, m.

The thickness of 15.62 m siltstone above 9# coal seam in Shancheng Coal Mine is the nearest equilibrium rock layer, M is 1.37 m, and K is 1.2. According to formula (4), the equilibrium height of surrounding rock H_b is 22.47 m, and the minimum distance between 3# coal seam and 9# coal seam is 53.5 m, which is above the equilibrium rock stratum of 9# coal seam.

Based on the above three determination methods, the 3#coal seam of Shancheng Coal Mine will be located on the fracture zone formed after the mining of 9# coal seam

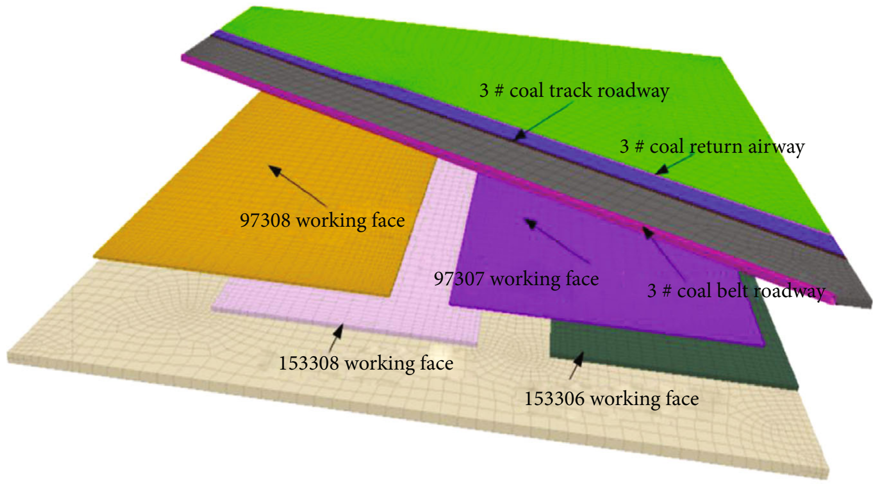


FIGURE 4: Figure of numerical model.

TABLE 1: Physical and mechanical parameter table of coal and rock mass.

Serial number	Lithologic characters	Thickness/m	Density/ (kg/m^3)	Bulk modulus/GPa	Shear modulus/GPa	Cohesion/MPa	Angle of friction/°	Resistance strength/MPa
1	Mudstone	2.8	2250	7	4	2.1	15	1.8
2	3# coal seam	6.3	1400	5	3.2	1.8	20	0.8
3	Mudstone	8.2	2250	7	4	2.1	15	1.8
4	Post office box stone	2.7	2530	18.6	12.4	4.6	36	3.2
5	Mudstone	5.8	2250	7	4	2.1	15	1.8
6	Limestone	4.6	2510	8	6	2.1	32	2.0
7	Siltstone	15.62	2450	21.2	16.8	4.0	38	4.1
8	Mudstone	8.6	2250	7	4	2.1	15	1.8
9	Post office box stone	9.2	2530	18.6	12.4	4.6	36	3.2
10	9# coal seam	1.3	1400	5	3.2	1.8	20	0.8
11	Post office box stone	6.79	2530	18.6	12.4	4.6	36	3.2
12	Medium grained sandstone	10.76	2430	20	13.6	4.5	32	2.8
13	Mudstone	3.66	2250	7	4	2.1	15	1.8
14	Limestone	10.17	2510	8	6	2.1	32	2.0
15	15# coal seam	2.66	1400	5	3.2	1.8	20	0.8
16	Mudstone	4.24	2250	7	4	2.1	15	1.8

and 15# coal seam, with good integrity and continuity. Therefore, upward mining can be carried out.

3.2. Numerical Simulation Analysis. In order to further clarify the failure characteristics of overlying strata, according to the actual mining situation of coal seam in Shancheng Coal Mine, FLAC3D [26–27] was used to establish a three-dimensional numerical model, as shown in Figure 4. The geometric size of the model is $X \times Y \times Z = 460\,\text{m} \times 460\,\text{m} \times 107.5\,\text{m}$, with a total of 287200 units and 310240 nodes. The displacement boundary control method is used to control the front, rear, left and right sides, and below. The front, rear, and left and right sides are movable in the vertical direction, and the bottom is fixed. The stress boundary is used above. The buried depth is 300 m, and the vertical load of 7.5 MPa is applied to the upper rock strata. The lateral pressure coefficient λ is 1.2, and the physical and mechanical properties of coal and rock mass are obtained through the reduction of rock mass classification method GSI [28] based on the laboratory coal and rock sample experiment, as shown in Table 1.The mining sequence is as follows: 97307 working face →302mining area roadway→97308 working face→153306 working face→153308 working face. The failure characteristics of overlying strata and the change of plastic zone of 3# coal seam under different advancing distances of working faces of underlying 9# and 15# coal seams are simulated and analyzed.

In the mining process of 9# coal seam, the variation characteristics of plastic zone of 3# coal seam are shown in Figures 5–6. It can be seen that when the 97307 working face

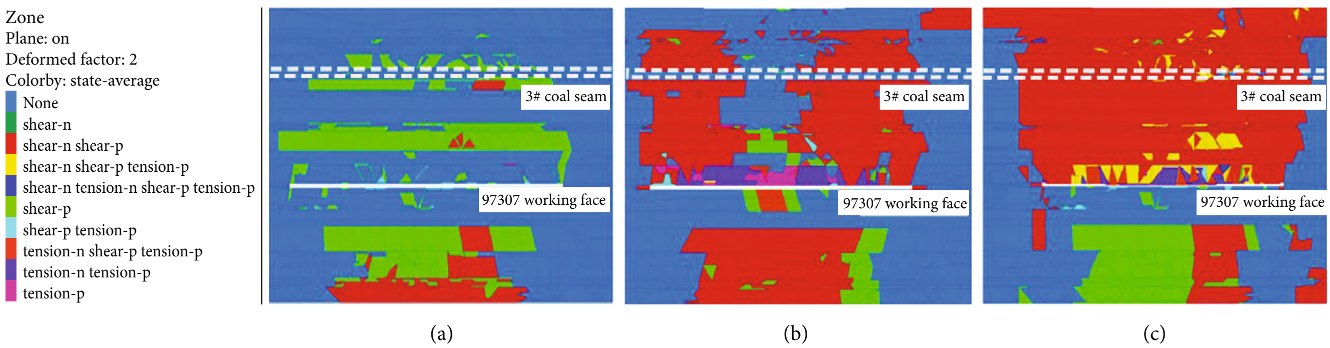


Figure 5: Cloud image of plastic zone in no. 3 coal seam during mining of 97307 working face. (a) Working face advancing 80 m; (b) working face advancing 160 m; (c) working face advancing 240 m.

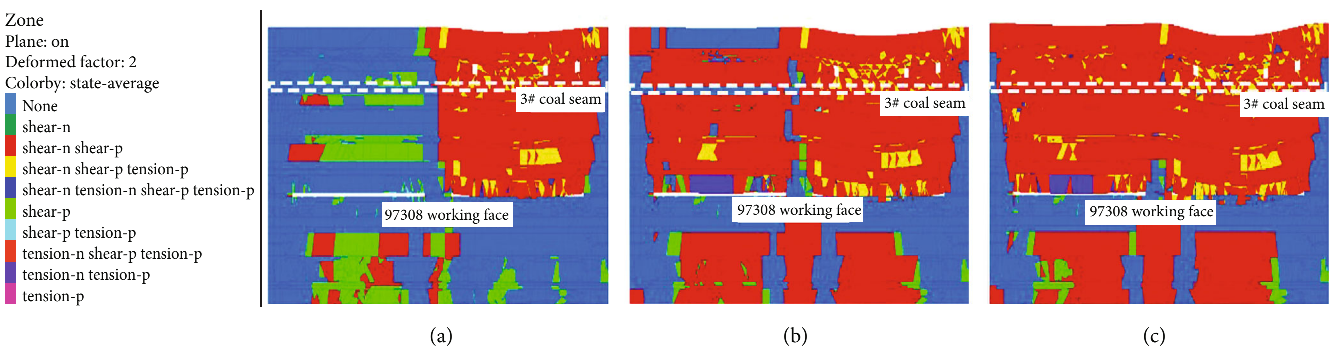


Figure 6: Cloud image of plastic zone in no. 3 coal seam during mining of 97308 working face. (a) Working face advancing 80 m; (b) working face advancing 160 m; (c) working face advancing 240 m.

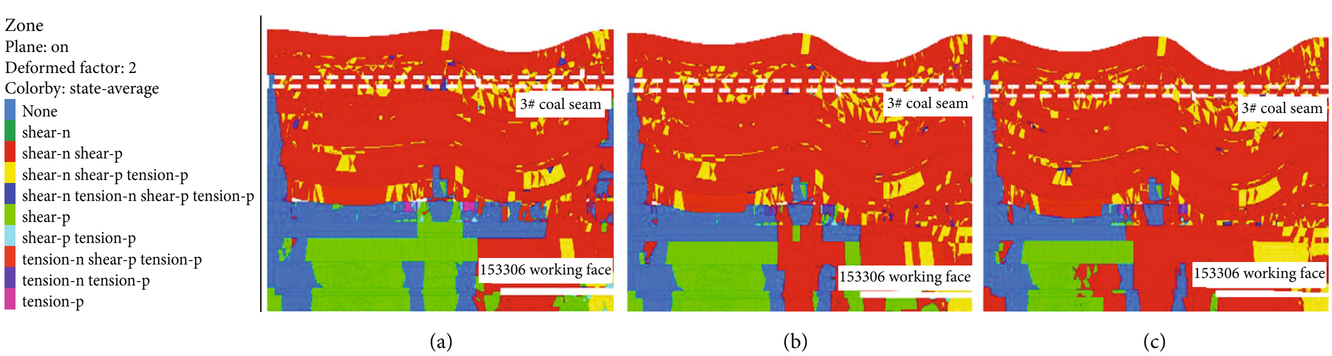


Figure 7: Cloud image of plastic zone in no. 3 coal seam during mining of 153306 working face. (a) Working face advancing 80 m; (b) working face advancing 160 m; (c) working face advancing 240 m.

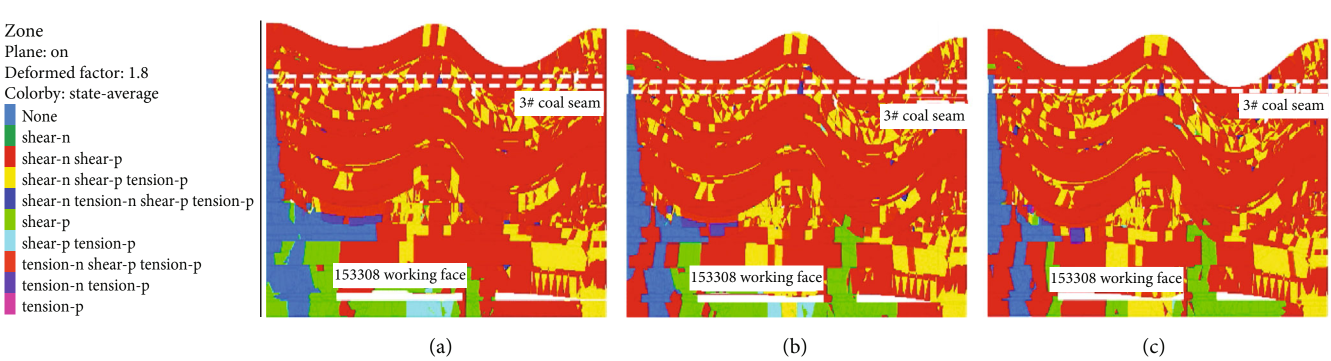


Figure 8: Cloud image of plastic zone in no. 3 coal seam during mining of 153308 working face. (a) Working face advancing 80 m; (b) working face advancing 160 m; (c) working face advancing 240 m.

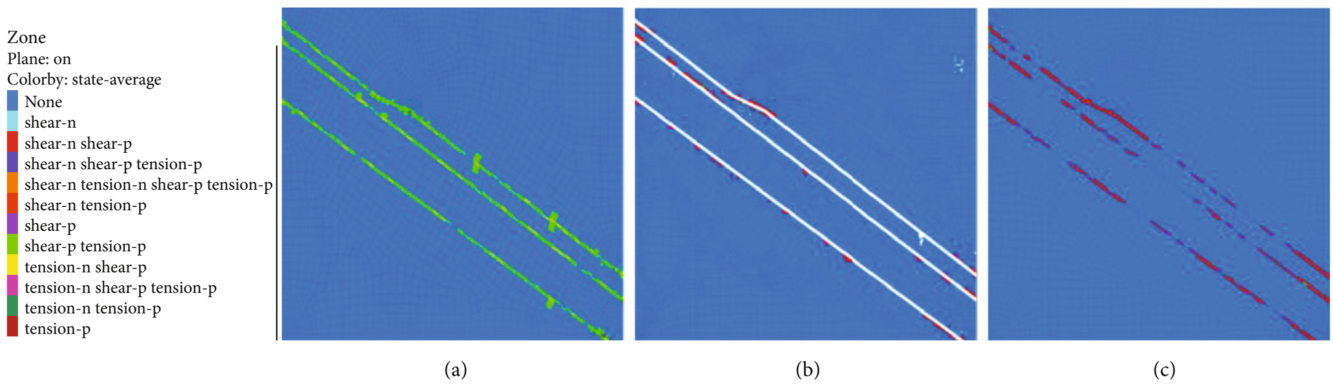


Figure 9: Distribution of plastic zone of roadway in 302 mining area during mining of 97307 working face. (a) Plastic zone of 3# coal roadway roof; (b) plastic zone of two sides of 3# coal roadway; (c) plastic zone of 3# coal roadway floor.

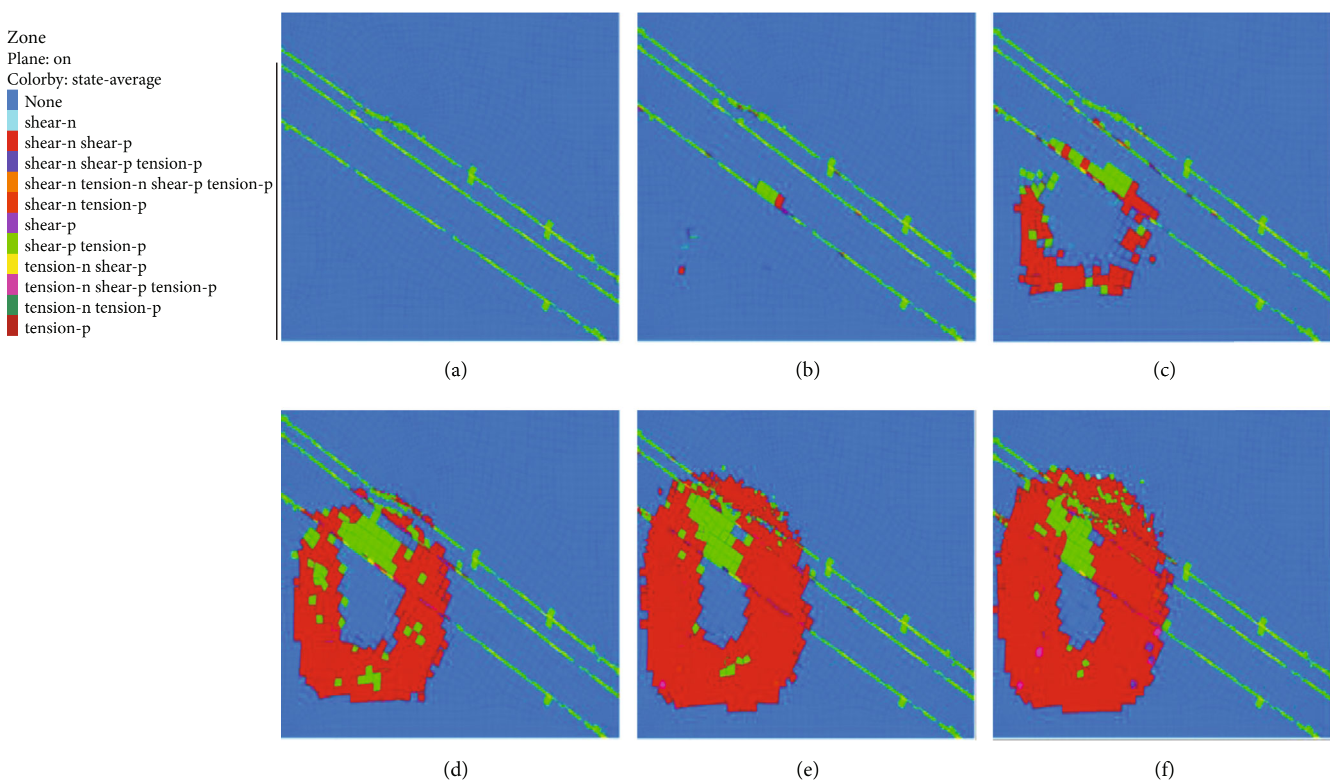


Figure 10: The roof plastic zone of 3 coal roadway during the advancing period of 97308 working face. (a) Working face advancing 120 m; (b) working face advancing 160 m; (c) working face advancing 200 m; (d) working face advancing 240 m; (e) working face advancing 280 m; (f) working face advance over 280 m.

advances 80 m, the plastic zone of 3# coal seam begins to develop. When it advances to 160 m, the plastic zone develops obviously, but the range of plastic zones on both sides is not much different. As shown in Figure 5(b), when the advancing is 240 m, the plastic zone develops stably. When the 97308 working face is pushed 160 m, the plastic zone of the adjacent 97307 working face is penetrated, as shown in Figure 6(b). When the working face is pushed 240 m, the overlying strata show overall bending and subsidence, as shown in Figure 6(c).

In the process of 15# coal seam mining, the variation characteristics of plastic zone of 3# coal seam are shown in Figures 7–8. It can be seen that when the 153306 working face advances 80 m, the plastic zone of 3# coal seam has been fully developed, and the overlying strata show overall bending subsidence, as shown in Figure 7(a). During the advancing process of 153308 working face, the deformation of overlying strata is more obvious than that of 153306 working face, showing continuous bending subsidence.

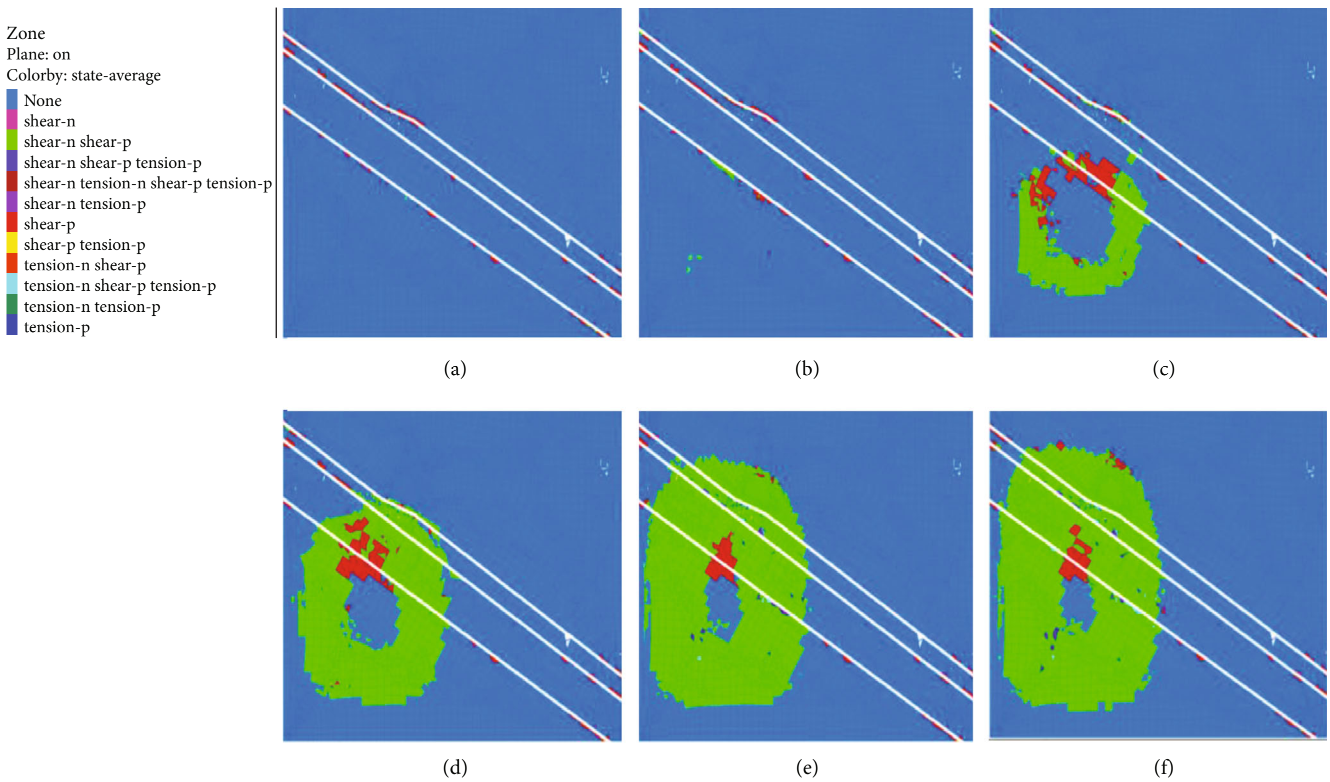


Figure 11: Plastic zone of side of 3 coal roadway during advancing of 97308 working face. (a) Working face advancing 120 m; (b) working face advancing 160 m; (c) working face advancing 200 m; (d) working face advancing 240 m; (e) working face advancing 280 m; (f) working face advance over 280 m.

In summary, after the mining of the underlying 9# and 15# coal seams, a large range of plastic failure occurred in the overlying strata, but the upper 3# coal seam was in its bending subsidence zone as a whole, with good continuity and no step dislocation. Therefore, 3# coal seam upward mining is feasible.

4. Repair Opportunity of Preparatory Roadway in Upper Coal Seam

The above research shows that 3# coal seam can be mined upward. However, this mining method is easy to make the upper coal seam roadway deform to different degrees due to the influence of the mining of the underlying coal seam, which increases the difficulty of roadway maintenance. Therefore, it is necessary to analyze the influence range of the mining of the underlying coal seam working face on the upper coal seam preparatory roadway, so as to determine the reasonable repair time. The deformation of roadway surrounding rock is essentially the formation and development of surrounding rock plastic zone. Therefore, based on the Section 3.2 numerical model, the change of plastic zone of roadway in upper coal seam during the mining process of 9# coal seam is studied.

During the mining process of 97307 working face, the change of plastic zone of roadway in 302 mining area is shown in Figure 9. It can be seen that the roadway in 302 mining area is basically not affected by the mining of lower coal seam, and plastic failure occurs only in a small range of shallow surrounding rock of this roadway. Therefore, the influence of 97307 working face mining on the stability of roadway in upper coal seam mining area can be ignored.

During the mining process of 97308 working face, the change of plastic zone of roadway in 302 mining area is shown in Figures 10–12. It can be seen that the roadway in 302 mining area is basically not affected by the mining of underlying coal seam before advancing 200 m in 97308 working face, and the plastic zone is only caused by the excavation of the roadway itself. As shown in Figures 10(a) and 10(b), when advancing 280 m, dense plastic zones appear in the surrounding rock of the roadway. As shown in Figure 10(f), the plastic zone of belt roadway in 302 mining area is about 150 m, the plastic zone of track roadway is about 135 m, and the plastic zone of return air roadway is about 120 m, and after advancing 280 m, the plastic zone of roadway is no longer obviously increased.

From the above analysis, it can be seen that the roadway in the mining area of 3# coal seam is less affected by the mining of 97307 working face. When the 97308 working face advances 200~280 m, the plastic zone of the roadway in the 302 mining area changes significantly, and the deformation of the surrounding rock of the roadway is severe, as shown in Figure 13. Therefore, the roadway repair should be carried out after the 97308 working face is pushed over 280 m.

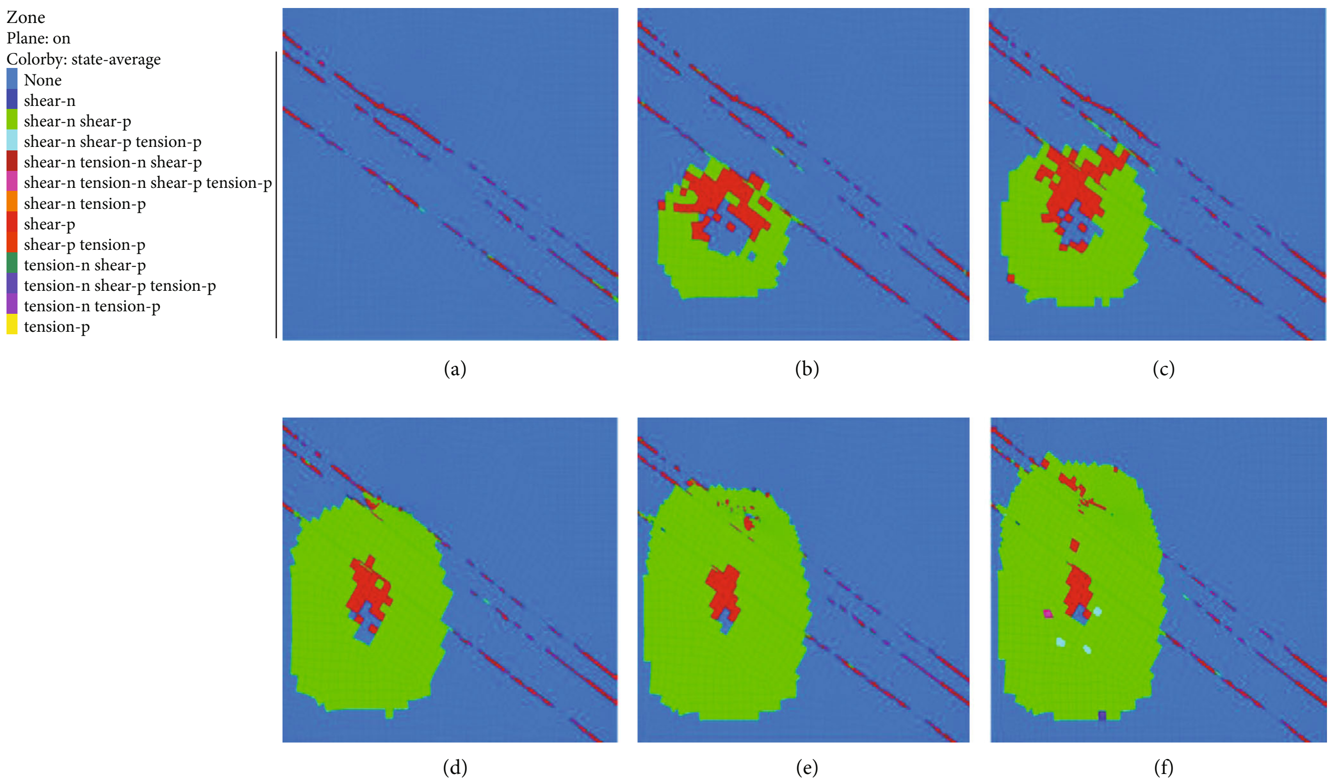


FIGURE 12: Plastic zone of 3 coal roadway floor during advancing of 97308 working face. (a) Working face advancing 120 m; (b) working face advancing 160 m; (c) working face advancing 200 m; (d) working face advancing 240 m; (e) working face advancing 280 m; (f) working face advance over 280 m.

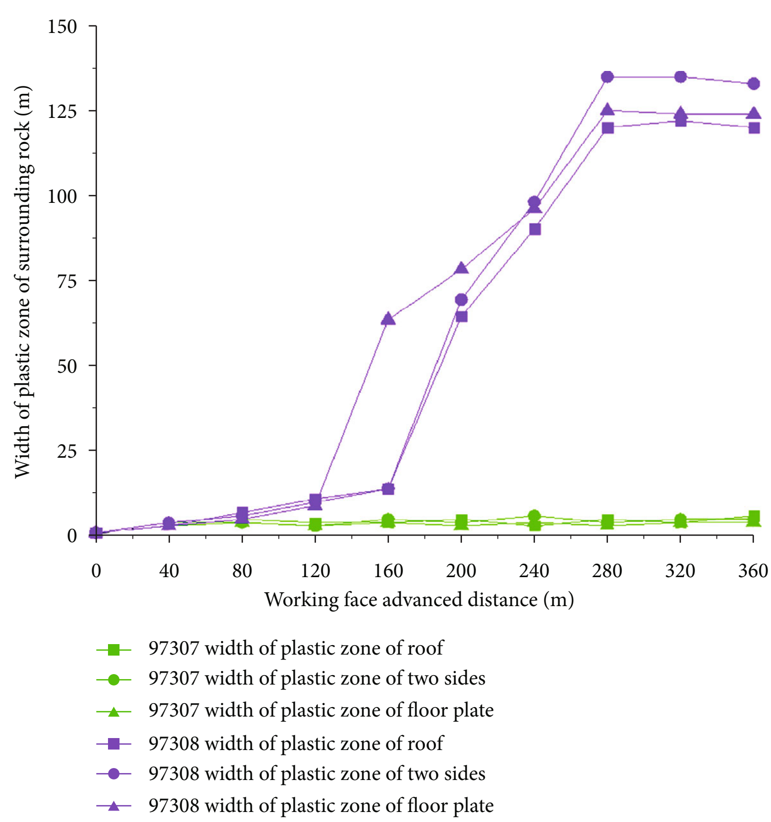
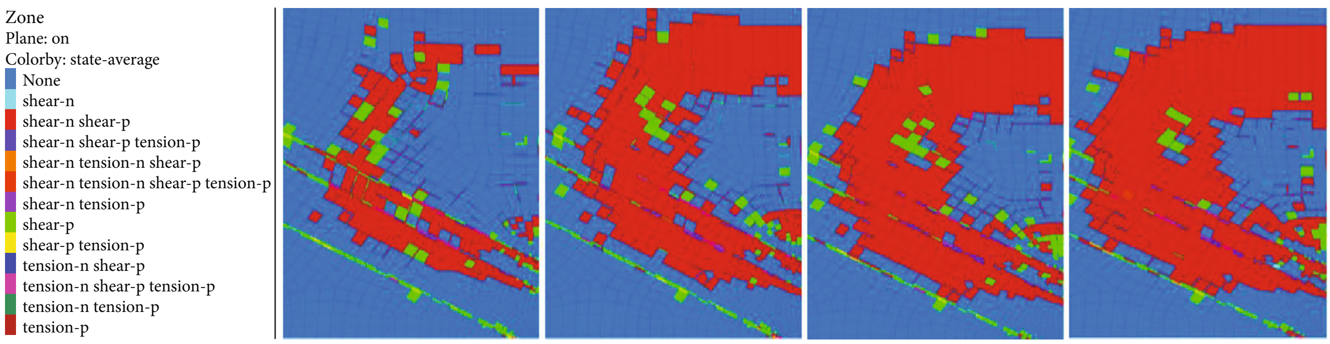
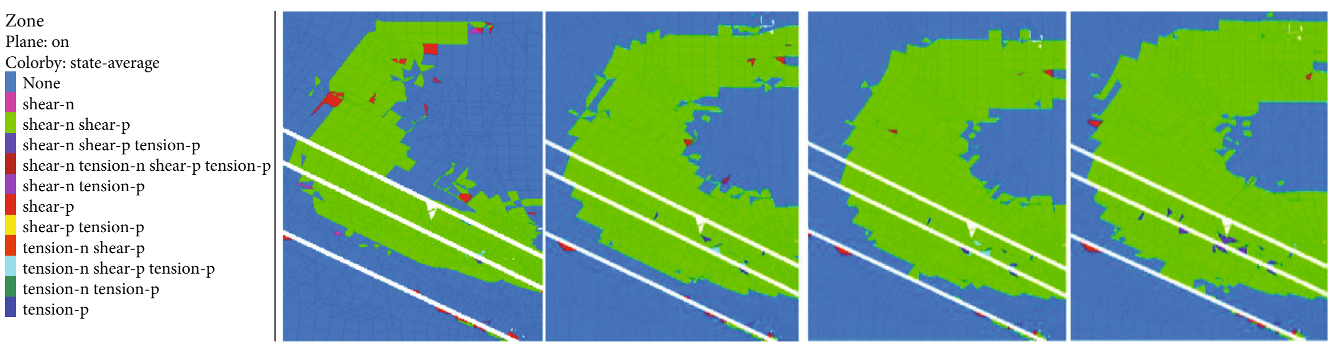


FIGURE 13: Changes of plastic zone width of roadway during mining of 9# coal seam.



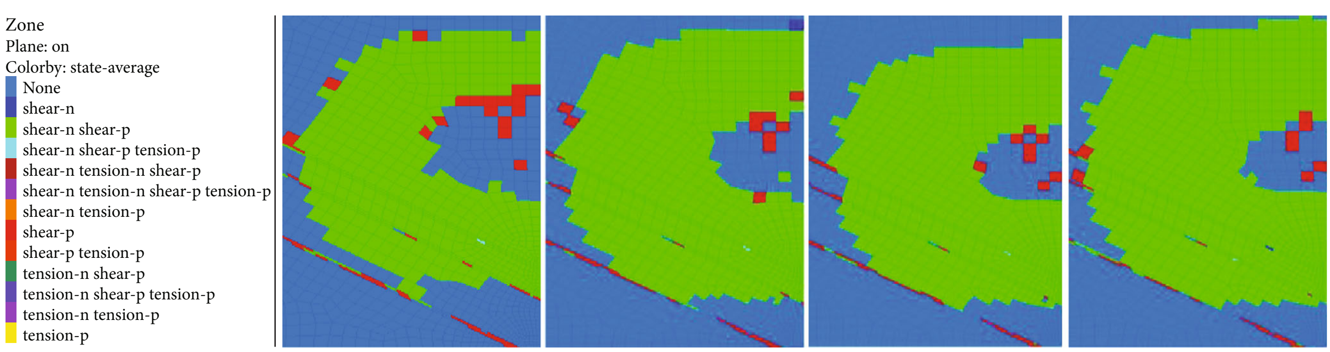
(a) (b) (c) (d)

Figure 14: The plastic zone change of roadway roof in 302 mining area when the cutting position is 300 m ahead of schedule. (a) Working face advancing 40 m; (b) working face advancing 80 m; (c) working face advancing 120 m; (d) working face advancing 160 m.



(a) (b) (c) (d)

Figure 15: The change of plastic zone in two sides of roadway in 302 mining area when the cutting position is 300 m ahead of schedule. (a) Working face advancing 40 m; (b) working face advancing 80 m; (c) working face advancing 120 m; (d) working face advancing 160 m.



(a) (b) (c) (d)

Figure 16: Changes of plastic zone of roadway floor in 302 mining area when the cutting position is 300 m ahead of schedule. (a) Working face advancing 40 m; (b) working face advancing 80 m; (c) working face advancing 120 m; (d) working face advancing 160 m.

5. Reasonable Open Cut Position in Lower Coal Seam Working Face

The cutting position of the underlying coal seam has a great influence on the stability of the surrounding rock of the upper roadway. Therefore, it is necessary to determine the reasonable position of the open-off cut in the underlying coal seam to reduce the influence of the lower coal seam mining on the stability of the upper coal seam roadway. Based on the above model, this section simulates and analyzes the variation characteristics of plastic zone of roadway in mining area of 3# coal seam when the cut of 153308 working face in 15# coal seam advances to 300 m, 340 m, and 380 m.

When the cutting position of 153308 working face is 300 m ahead of schedule, the plastic zone change of roadway in mining area 302 is shown in Figures 14–16. It can be seen that when the working face advances 40 m, only the plastic

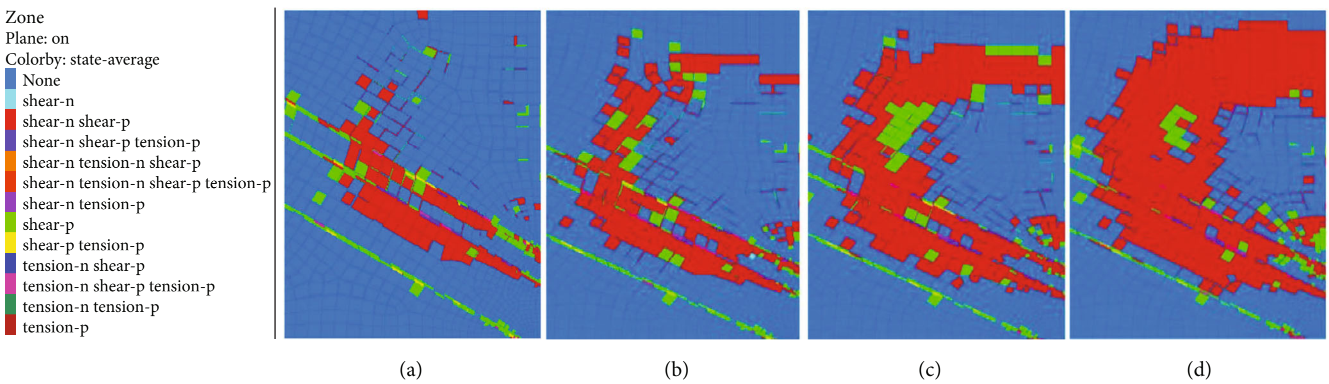


Figure 17: The plastic zone change of roadway roof in 302 mining area when the cutting position is 340 m ahead of schedule. (a) Working face advancing 40 m; (b) working face advancing 80 m; (c) working face advancing 120 m; (d) working face advancing 160 m.

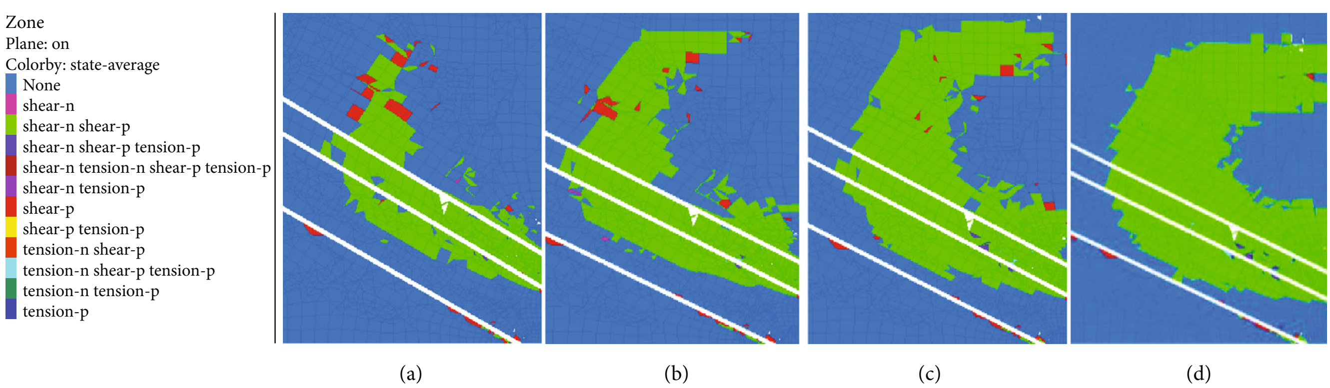


Figure 18: The change of plastic zone in two sides of roadway in 302 mining area when the cutting position is 340 m ahead of schedule. (a) Working face advancing 40 m; (b) working face advancing 80 m; (c) working face advancing 120 m; (d) working face advancing 160 m.

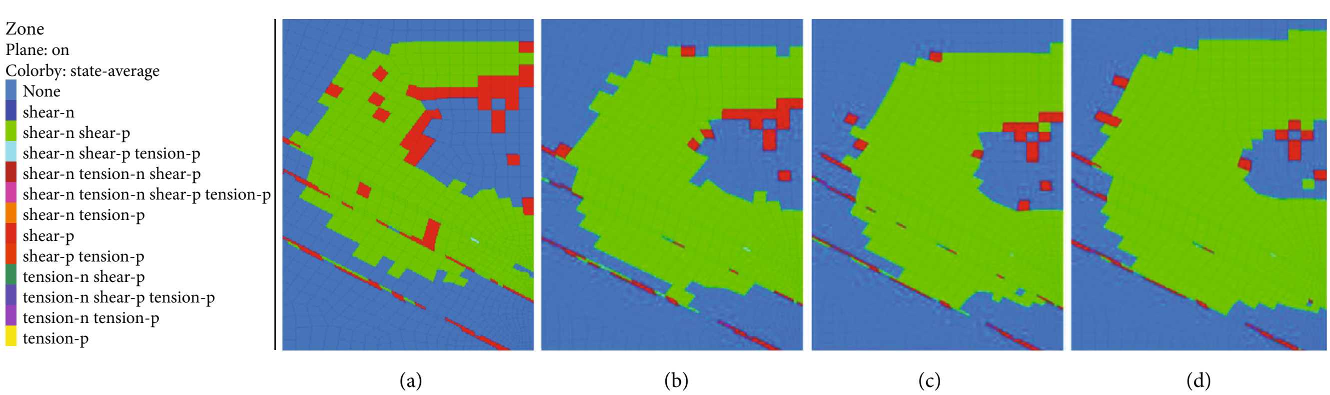


Figure 19: Change of plastic zone of roadway floor in 302 mining area when cutting position advanced to 340 m. (a) Working face advancing 40 m; (b) working face advancing 80 m; (c) working face advancing 120 m; (d) working face advancing 160 m.

zone of track roadway and return airway develops in 302 mining area. When the working face advances 80~120 m, the belt roadway in 302 mining area begins to be affected by mining, and the plastic zone range of track roadway and return airway increases. When the working face advances 160 m, the plastic zone range of roadway in 302 mining area is the largest, as shown in Figures 14(d), 15(d), and 16(d), the plastic zone range of belt roadway is about 70 m, the plastic zone range of track roadway is about 95 m, and the plastic zone range of return airway is about 100 m.

When the cutting position of 153308 working face is advanced by 340 m, the change of plastic zone of roadway in 302 mining area is shown in Figures 17–19. It can be seen

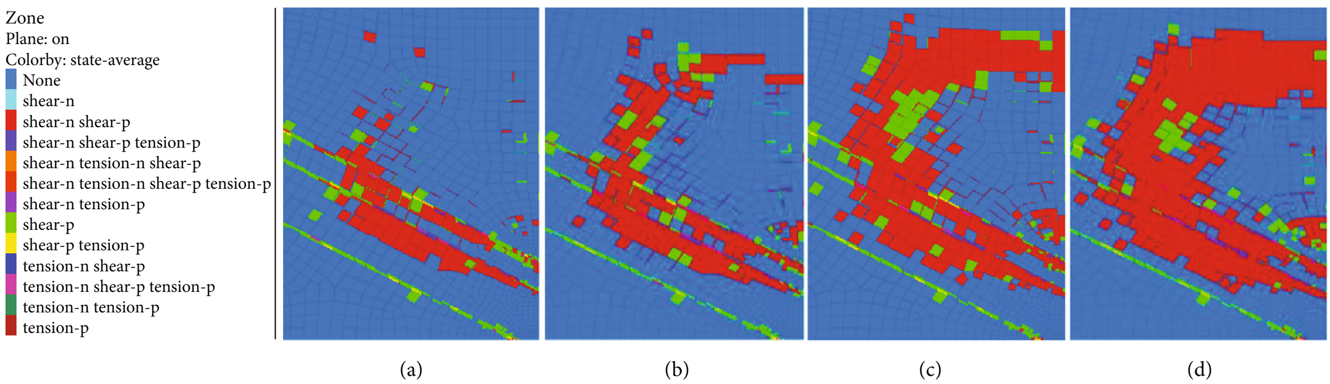


Figure 20: The plastic zone change of roadway roof in 302 mining area when the cutting position is 380 m ahead of schedule. (a) Working face advancing 40 m; (b) working face advancing 80 m; (c) working face advancing 120 m; (d) working face advancing 160 m.

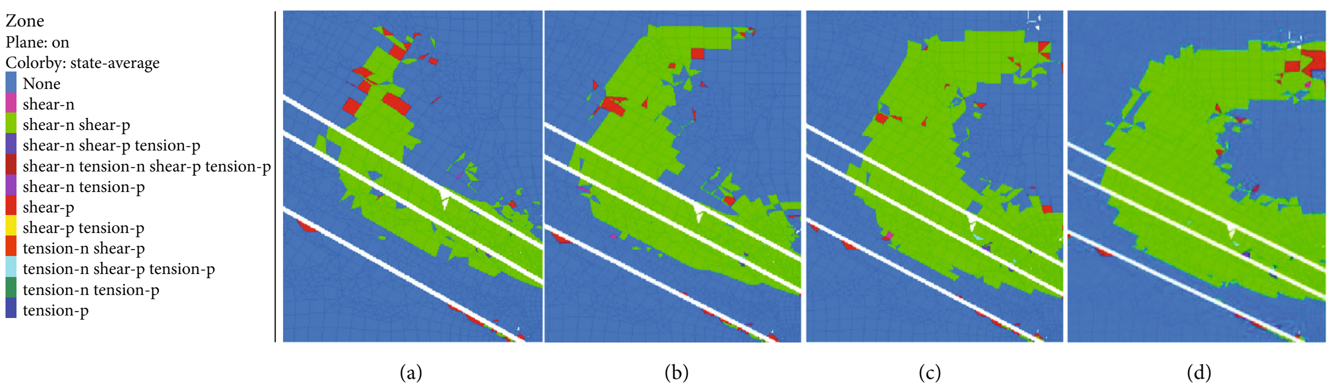


Figure 21: The change of plastic zone in two sides of roadway in 302 mining area when the cutting position is 380 m ahead of schedule. (a) Working face advancing 40 m; (b) working face advancing 80 m; (c) working face advancing 120 m; (d) working face advancing 160 m.

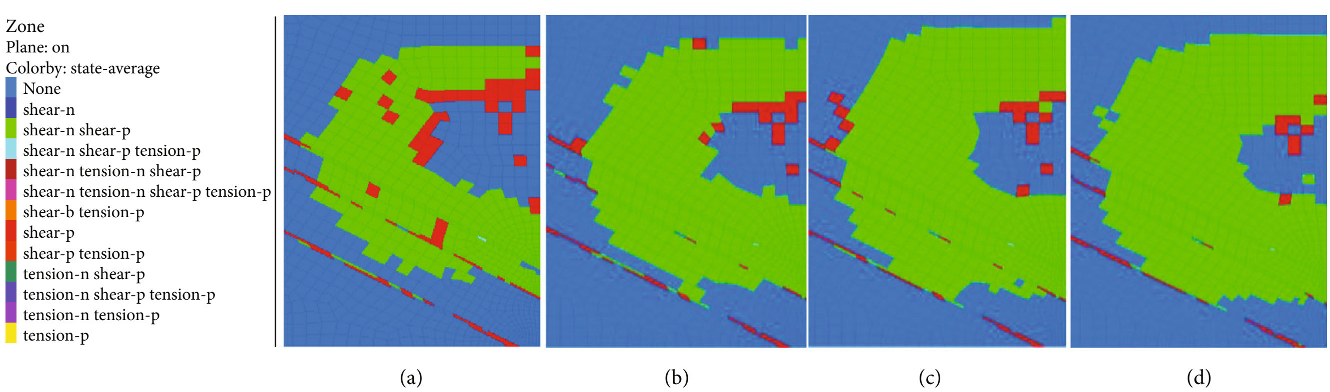


Figure 22: The change of plastic zone of roadway floor in 302 mining area when the cutting position is 380 m ahead of schedule. (a) Working face advancing 40 m; (b) working face advancing 80 m; (c) working face advancing 120 m; (d) working face advancing 160 m.

that the change of plastic zone of roadway in 302 mining area is reduced by the influence of lower coal seam mining. When the working face is advanced by 80 m, only the plastic zone of track roadway and return airway develops. When the working face is advanced by 120 m, the plastic zone of belt roadway in 302 mining area begins to develop, and the plastic zone range of track roadway and return airway continues to increase. When the working face is advanced by 160 m, the plastic zone range of roadway is the largest, as shown in Figures 17(d), 18(d), and 19(d), the plastic zone range of belt roadway is about 35 m. The plastic zone of track roadway is about 60 m, and the plastic zone of return airway is about 65 m.

When the cutting position of 153308 working face is 380 m in advance, the plastic zone change of roadway in 302 mining area is shown in Figures 20–22. It can be seen

Table 2: Plastic zone width of roadway surrounding rock with different open-off cut position.

(a)

Working face advanced distance/m	Open-off cut position advanced to 300 m								
	Belt roadway/m			Track roadway/m			Return air roadway/m		
	Roof	Two sides	Floor plate	Roof	Two sides	Floor plate	Roof	Two sides	Floor plate
0	0	0	0	0	0	0	0	0	0
40	13	12	13	52	75	57	59	78	63
80	42	20	41	86	81	69	90	87	72
120	64	26	58	91	86	82	95	92	83
160	68	29	62	94	93	94	98	97	98
200	67	27	63	92	94	93	100	97	96
240	67	25	62	93	95	93	99	97	96

(b)

Working face advanced distance/m	Open-off cut position advanced to 340 m								
	Belt roadway/m			Track roadway/m			Return air roadway/m		
	Roof	Two sides	Floor plate	Roof	Two sides	Floor plate	Roof	Two sides	Floor plate
0	0	0	0	0	0	0	0	0	0
40	3	3	7	29	41	33	33	39	37
80	8	5	18	38	52	42	43	48	48
120	24	9	28	43	56	50	49	53	55
160	36	14	33	60	62	58	65	66	64
200	36	15	32	61	62	58	64	65	63
240	35	14	32	61	62	57	63	65	63

(c)

Working face advanced distance/m	Open-off cut position advanced to 380 m								
	Belt roadway/m			Track roadway/m			Return air roadway/m		
	Roof	Two sides	Floor plate	Roof	Two sides	Floor plate	Roof	Two sides	Floor plate
0	0	0	0	0	0	0	0	0	0
40	2	4	6	28	37	31	30	34	38
80	7	7	16	39	48	43	42	43	47
120	21	10	24	45	53	49	51	48	53
160	33	12	31	62	59	59	67	63	63
200	34	14	33	62	60	58	66	65	64
240	33	14	32	60	59	58	65	65	64

that the plastic zone change of roadway in 302 mining area is not much different from that when the cutting position is 340 m in advance. When the working face advances 160 m, the maximum range of plastic zone of belt roadway is about 30 m, the maximum range of plastic zone of track roadway is about 60 m, and the maximum range of plastic zone of return airway is about 65 m.

From the above analysis, it can be seen that when the cutting position of 153308 working face is 340 m and 380 m ahead of schedule, the plastic zone of roadway in 302 mining area has a small variation range, as shown in Table 2. Under the premise of ensuring safe production, in order to save coal resources, the reasonable open-off cut position of 153308 working face in 15# coal seam should be advanced to 340 m.

6. Engineering Application Effect

Shancheng Coal Mine reworked the roadway in 302 mining area after 280 m advancement of 97308 working face in 9# coal seam. In the late mining process of 9# coal seam working face, the maximum subsidence of roadway roof in 302 mining area was 48 mm, the maximum displacement of two sides was 45 mm, the maximum floor heave was 25 mm, and the deformation of roadway was small, as shown in Figure 23(a). During the mining of 15# coal seam, the cutting position of 153308 working face was advanced to 340 m. During the mining of working face, the maximum subsidence of roadway roof increased by 25 mm, the maximum displacement of two sides increased by 25 mm, and the maximum floor heave

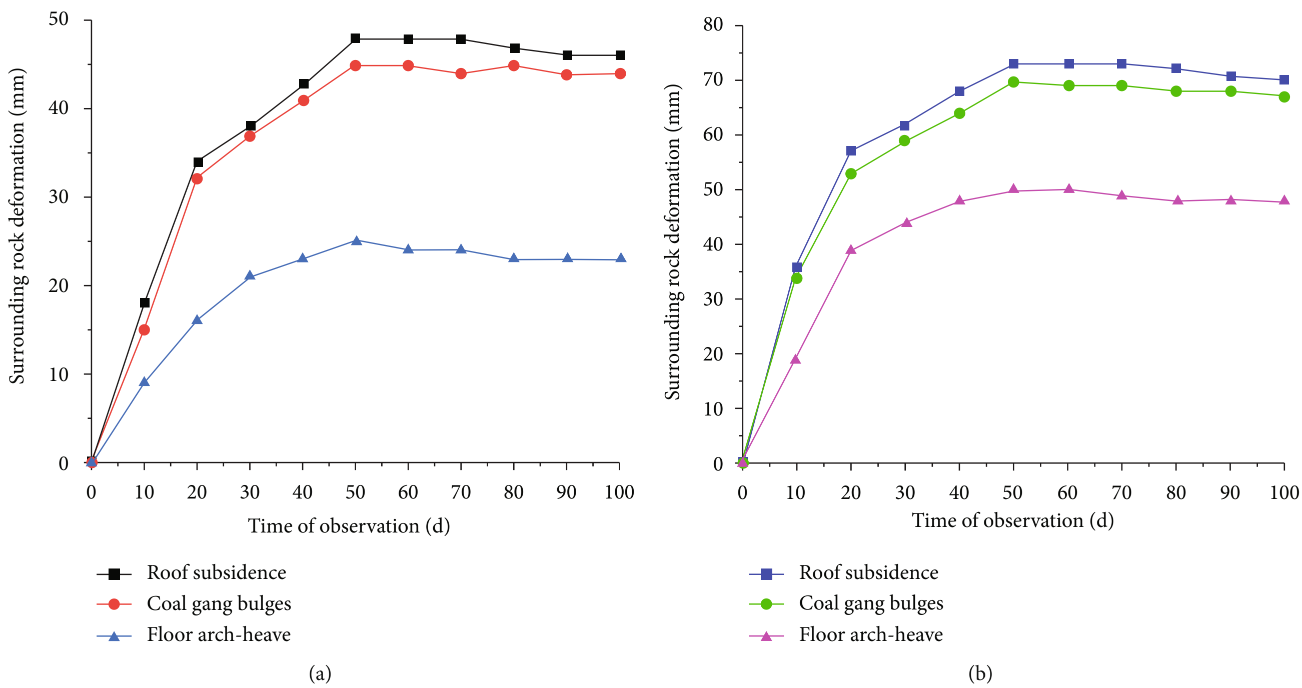


Figure 23: Deformation of roadway surrounding rock during mining of underlying coal seam after repair. (a) Deformation of roadway in mining area during 9# coal seam mining and deformation of roadway in mining area during 15# coal seam mining.

increased by 15 mm, as shown in Figure 23(b). It can be seen that after reasonable mining parameters are adopted, the rework of roadway is avoided and the safety production requirements are met.

7. Conclusions

(1) The theoretical formula and numerical simulation analysis show that after the mining of the working face of the underlying coal seam in Shancheng Coal Mine, the maximum height of the caving zone is 15.72 m and the maximum height of the fracture zone is 35.68 m. The minimum distance between 3# coal seam and underlying coal seam is 53.5 m. 3# coal seam is located above the fracture zone of underlying coal seam, showing overall subsidence, good continuity, and upward mining

(2) The surrounding rock deformation of upper coal seam roadway increases first and then tends to be stable due to the mining of underlying coal seam. Before the 97308 working face of Shancheng Coal Mine advances to 200 m, the plastic failure of roadway in 302 mining area occurs only in a small range of shallow surrounding rock. When advancing 200~280 m, the plastic zone range gradually increases and then stabilizes. The maximum plastic zone of belt roadway is about 150 m, the maximum plastic zone of track roadway is about 135 m, and the maximum plastic zone of return airway is about 120 m. The roadway repair in the upper coal seam mining area should be carried out after 280 m of the 97308 working face to avoid the severe deformation period affected

(3) In the upward mining process, the cutting position of the working face in the underlying coal seam has a significant influence on the variation range of the plastic zone of the roadway in the upper coal seam. When upward mining in Shancheng Coal Mine, the cutting position of 153308 working face should be advanced to at least 340 m. Considering the saving of coal resources, the cutting position of 153308 working face should be advanced to 340 m

(4) The field observation results show that after the implementation of the reasonable mining parameters determined in this paper in Shancheng Coal Mine, the upper coal seam roadway is less affected by the mining activities of the underlying coal seam in the later period, and the deformation of the surrounding rock of the roadway meets the production requirements, which avoids the problem of repeated repair of the roadway

Data Availability

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Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

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