

Article

A Study on the Deformation Mechanism of the Rock Surrounding a Weakly Cemented Cross-Layer Roadway, under Tectonic Stress

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Abstract: Maintaining the stability of the surrounding rock is an important prerequisite in ensuring the safe and efficient construction of underground mines—in particular, the surrounding rock of the cross-layer roadway, which is a combination of different media with different lithologies. Numerical models were established to investigate the effects of the different lateral pressure coefficients (λ), the angle (α) between the roadway and the maximum horizontal principal stress, and typical lithological combinations on the deformation of the surrounding rock of weakly cemented roadways. The main outcomes obtained from our research indicated the following: (1) under the action of tectonic stress, the focus should be on strengthening the roof of the roadway support of the slab, which is conducive to the stability of the surrounding rock; (2) roadway deformation and failure for the cases $\lambda < 1.5$ are approximately symmetrically distributed, whereas those for the cases $\lambda > 1.5$ are asymmetric; (3) roadway deformation and failure for the cases $\alpha < 45^\circ$ are approximately symmetrically distributed, whereas those for the cases $\alpha > 45^\circ$ are asymmetric; (4) tectonic stress has an important influence on stress redistribution, deformability, and damage in cross-layer roadways; and (5) when excavating cross-layer roadways under the action of tectonic stress, the concentrated stress around the end of the working face (especially the bottom corner) should be reduced. The research results provide insights for the roadway layout through coal seam and cross-layer excavation and deepen the understanding of the deformation mechanism of weakly cemented cross-layer roadway under tectonic stress.

Keywords: tectonic stress; weakly cemented stratum; cross-layer roadway; asymmetric deformation; deformation mechanism



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1. Introduction

With the gradual depletion of shallow coal resources in eastern China, China's coal resource development strategy is progressively shifting to western regions. Xinjiang is rich in coal resources, but its coal seam occurrence conditions are quite different from those in the eastern mining areas [1]. The coal-measure strata in this area are mainly Jurassic and Cretaceous, with a relatively late diagenetic period, which are generally characterized by weakly cemented strata and obvious regional tectonic stress [1–4]. These factors present a new challenge to the stability control of a roadway's surrounding rock. The process of a roadway's excavation in this area will be comprehensively affected by a variety of adverse factors, which will cause serious damage to the surrounding rock [5,6]. Therefore, it is important to study the deformation mechanism of the rock that surrounds weakly cemented cross-layer roadways, which are under tectonic stress, to ensure safe and efficient production in western mines.

The deformation and failure of roadways under tectonic stress have been a prominent topic in the literature. Based on field measurements, a theoretical analysis, and numerical simulation, Kang et al. and Wang et al. [7,8] analyzed the stress distribution law in the

tectonic area. Furthermore, Lu et al. [9] studied the distribution law of the plastic zones in a roadway's surrounding rock, which was affected by tectonic stress. Wang et al. [10] measured the in situ stress in a mining area and analyzed the mechanism of the asymmetric large deformation failure in its roadway, due to the complex geological stress environment in the area. Moreover, Xue et al. [11] established a numerical simulation model with discrete element UDEC software to reveal the effect of horizontal tectonic stress on a roadway's stress evolution, its fracture development mechanism, and its instability failure mechanism.

In addition, some scholars have studied the failure mechanism in the surrounding rocks of roadways by using a physical model test and a theoretical analysis. He et al. and Sun et al. [12–14] studied the deformation and failure mechanisms of the rocks surrounding roadways through a comprehensive analysis using a physical simulation, an infrared image, an experimental image, and a displacement field image. Tao et al. [15] compared and analyzed the failure characteristics of roadways with different dip angles that were under the action of tectonic stress. Shi et al. [16] analyzed the evolution mode and distribution characteristics of stress–strain roadway deformation and fracture through field-based geomechanical model tests. Yuan et al. [17] deduced the boundary equation of the plastic zone around deep roadways and analyzed the evolution law of the plastic zone shape and the relationship between the shape index and the surrounding rocks' stability. Guo et al. [18] analyzed the difference in the properties of rock strata under layered surrounding rock conditions, which can lead to “butterfly” failure in rocks that surround a roadway.

However, the stability of roadways excavated in non-uniform rocks (especially weakly cemented strata containing coal seams) characterized by lithology mutations has not been explicitly revealed.

Regarding the rock deformation mechanism in rocks that surround cross-layer roadways and weakly cemented roadways, Li et al. [19] established numerical models to study the mechanism of the tectonic stress direction's influence on the stability of an excavated roadway running through a coal seam. Feng et al. [20] studied the deformation characteristics of both the soft and hard rock contact zones when the tunnel crosses a complex stratum. Zhao et al. [21,22] established a numerical calculation model that considered the effect of the rock layer interface; analyzed the deformation mechanism of the roof separation of weakly cemented strata, revealed the deformation law of the roof, two sides, and the floor; derived the radius of the plastic zone of the surrounding rocks and the theoretical formula for calculating the associated stress field. Yu et al. [23] revealed the distribution law of the stress and plastic zones in the rock surrounding roadways and the characteristics of asymmetric deformation damage in roadways. Yang et al. [24] analyzed the characteristics and mechanisms of deformation and failure of the surrounding rocks.

Despite these great achievements, the effects of tectonic stress on the stability of cross-layer roadway excavations remain unknown. Thus, based on the engineering and geological conditions of the Weizigou mine, this research has adopted the methods of field measurements, indoor experiments, theoretical analysis, and numerical simulation to study the stress distribution, the plastic zone change, and the deformation and failure characteristics of the rocks that surround weakly cemented, cross-layer roadways—specifically, in terms of the magnitude and direction of the tectonic stress and of a typical cross-layer roadway. Therefore, this study can provide useful reference for the layout of roadways and the study of roadway deformation laws under similar engineering and geological conditions in western mining areas.

2. Engineering Background

2.1. Geological Conditions of the Test Roadway

In western China, many engineering projects are carried out in weakly cemented rock strata, which presents great challenges to underground engineering and mining engineering in this stratum. The design length of the centralized haulage way in the Weizigou mine is 1059.7 m. It is constructed from the sandstone in the roof of the B8 coal seam and up through the layer. The roadway passes through the sandstone and mudstone, which, in

turn, enter the B7 coal seam, and is then arranged along the B7 coal seam. The main average thickness of the B7 coal seam is approximately 6.49 m. The distribution of the roadway and the location of the centralized transportation roadway are shown in Figure 1 (the red area in the figure marks the test tunnel and the lithological distribution of the stratum).

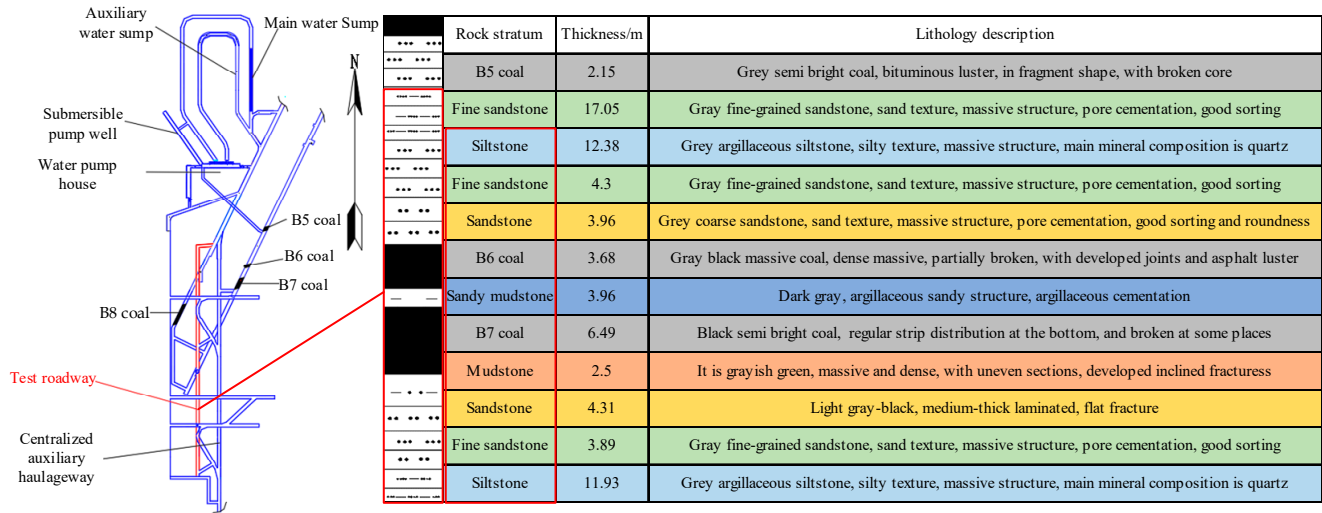


Figure 1. Plane location distribution and comprehensive histogram of underground roadways.

2.2. Deformation Characteristics of the Test Roadway's Surrounding Rock

The roadway section's form consisted of a straight wall and a semi-circular arch section, its digging slope was 17° – 19° , its width was 4.44 m and its net width was 4.20 m, its digging height was 3.52 m, and its net height was 3.3 m.

According to the results of the ground stress test, due to the existence of a certain angle between the test roadway and the maximum horizontal principal stress, the deformation of the rocks after the excavation was significant and had obvious asymmetrical deformation damage characteristics. According to the field observations, the specific deformation characteristics of the rocks surrounding the roadway were as follows:

- (1) The deformation of the surrounding rock was obvious during the roadway boring process: the roadway's slurry spraying body tore and cracked, the anchor pallets collapsed, the U-shaped steel bracket column's legs became bent and deformed, and the support structure failed locally;
- (2) During the construction of the cross-layer roadway, the coal cannon appeared at the roadway's working face, the deformation of the roadway's roof and floor was large, the phenomenon of the local bubble fall appeared, and the deformation of the ribs showed obvious asymmetric deformation characteristics;
- (3) According to the observation regarding the mining pressure on the site, the local stress concentration and deformation of the surrounding rocks were significant: there were flaky ribs and anchor failure, and the roadway was seriously damaged and had to be repaired many times, which made it difficult to meet the requirements that were necessary for the safe and efficient construction of the mine.

The purpose of this study is to analyze the deformation mechanism of the rock surrounding a weakly cemented roadway under the action of tectonic stress, and the results of the study can provide useful reference for roadway arrangement and roadway support under similar geological conditions.

3. Deformation Law of Weakly Cemented Roadway's Surrounding Rock, under the Action of Tectonic Stress

3.1. Methods

3.1.1. In Situ Stress Measurement

An in situ stress measurement technique, which is based on a CSIRO cell, was applied to the field measurements on the test roadway. The result of the measured point data showed that the ground stress type was $\sigma_H > \sigma_v > \sigma_h$. The maximum principal stress (near the horizontal direction) of the measuring point was nearly 12.89 MPa~20.98 MPa, and the average ratio of the maximum principal stress to the vertical stress was 1.60~1.88.

3.1.2. Theoretical Analysis

According to the maximum horizontal principal stress (σ_H), the minimum horizontal principal stress (σ_h) and the vertical principal stress (σ_v), the magnitude of the three values and the original rock stress field were divided into the following three different types: σ_H type; $\sigma_H > \sigma_h > \sigma_v$; σ_{Hv} type; $\sigma_H > \sigma_v > \sigma_h$; and σ_v type, $\sigma_v > \sigma_H > \sigma_h$ [25]. To grasp the influence of the tectonic stress on the stability of the roadway, the state of the ground stress was described by the lateral pressure coefficient, λ . λ was the ratio of horizontal principal stress to vertical stress, and the different values of λ characterized the roadway, which was subject to different tectonic stress fields. λ was specifically calculated as follows:

$$\sigma_x = \sigma_y = \frac{\mu}{1 - \mu} \sigma_z = \frac{\mu}{1 - \mu} \gamma H \quad (1)$$

$$\lambda = \frac{\mu}{1 - \mu} \quad (2)$$

where λ is the lateral pressure coefficient, μ is the rock Poisson's ratio, and the lead stress (σ_z) and the horizontal stress (σ_x, σ_y) are all the principal stresses.

3.2. Numerical Models and Simulation Schemes

A numerical calculation model was constructed to invert the stress distribution, the plastic zone changes, and the deformation and damage characteristics of the rocks surrounding the weakly cemented roadway, under the action of tectonic stress. This was based on the engineering and geological conditions of the Weizigou coal mine. As shown in Figure 2, the model's stratigraphic dip angle was 15° , the model's size was $L \times W \times H = 50 \text{ m} \times 50 \text{ m} \times 50 \text{ m}$, the test roadway was arranged in the center of the B7 coal seam, and the roadway's size was consistent with the actual size of the site.

The model restricted horizontal movement on the side and was fixed on the lower surface. A load of 7.78 MPa was applied on the upper surface to simulate the self-weight boundary of the overlying rock, and the tectonic stresses in the horizontal direction were expressed by different lateral pressure coefficients, λ . The Mohr–Coulomb criterion was used for the model calculation, and the physical and mechanical parameters of the rock formation were taken from the mine's geological report and the borehole data. The specific parameters are shown in Table 1.

In this paper, the deformation mechanism of the surrounding rock was studied under five working conditions with different lateral pressure coefficients (λ) of 0.5, 1.0, 1.5, 2.0, and 2.5. When $\lambda < 1$, the stress field was dominated by vertical stress; when $\lambda = 1$, there was a hydrostatic pressure state; and when $\lambda > 1$, a horizontal stress dominated.

Under the condition of keeping the vertical stress constant, the initial ground stress state of the rock surrounding the roadway, under the action of different tectonic stress magnitudes, was characterized by changing the lateral pressure coefficient (λ). The specific numerical simulation scheme is shown in Table 2.

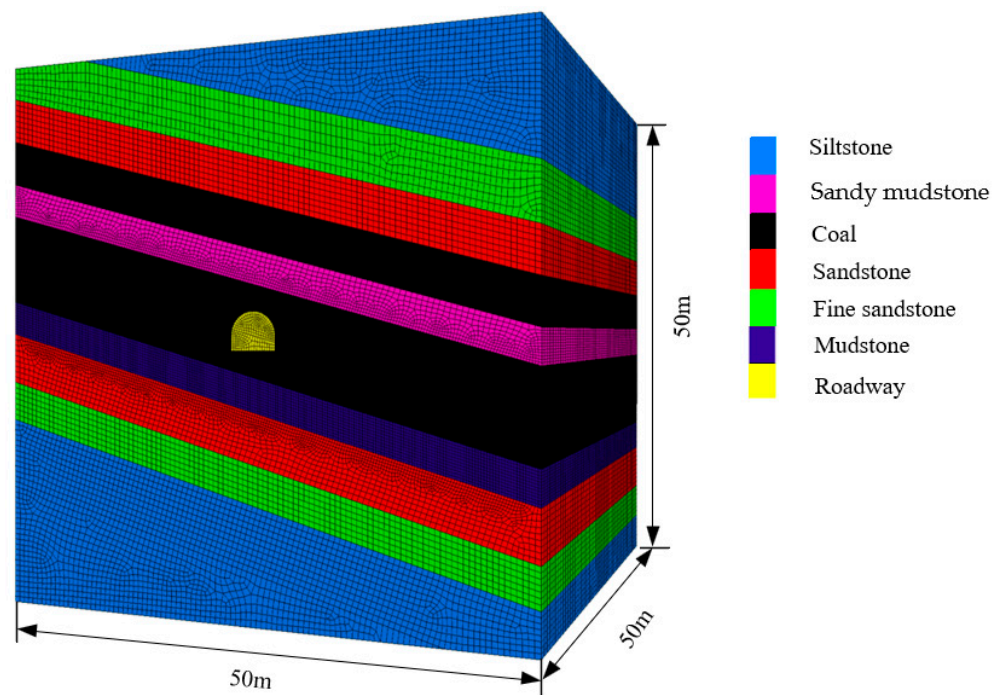


Figure 2. Initial numerical model diagram based on geological conditions.

Table 1. Physical and mechanical parameters of coal and rock.

Rock Character	Bulk Density (KN/m ³)	Tensile Strength (MPa)	Bulk Modulus (GPa)	Shear Modulus (GPa)	Cohesion (MPa)	Friction Angle (°)
Fine sandstone	2430	1.5	2.06	0.98	5.7	27.4
Siltstone	2570	1.65	2.56	1.28	5.55	40
Sandstone	2590	1.0	1.87	0.93	4.32	37.8
Sandy mudstone	2450	0.1	0.88	0.54	1.37	31
Mudstone	2350	0.15	0.85	0.46	1.45	38
Coal	1730	0.1	0.46	0.28	1.5	23

Table 2. Initial ground stress simulation schemes of different magnitudes.

Scheme No.	λ Value	σ_x	σ_y	σ_z
1	0.5	3.89	3.89	7.78
2	1.0	7.78	7.78	7.78
3	1.5	11.67	11.67	7.78
4	2.0	15.56	15.56	7.78
5	2.5	19.45	19.45	7.78

3.3. The Influence Law of Tectonic Stress Magnitude on the Evolution of the Plastic Zone of the Surrounding Rock

When simulating in FLAC3D using the plastic constructive model, the PLOT block state command can be used to display those areas where the stresses meet the yield criterion (or plastic zone) in order to see the extent of the potential damage area. The range of the plastic zone in this paper is expressed by the maximum failure depth, and its measuring method is FLAC's own measuring tool (shown as the distance between two selected points on the plot). The distribution of the plastic zone of the surrounding rock in the roadways of weakly cemented strata, under the condition of different lateral pressure coefficients, is shown in Figure 3.

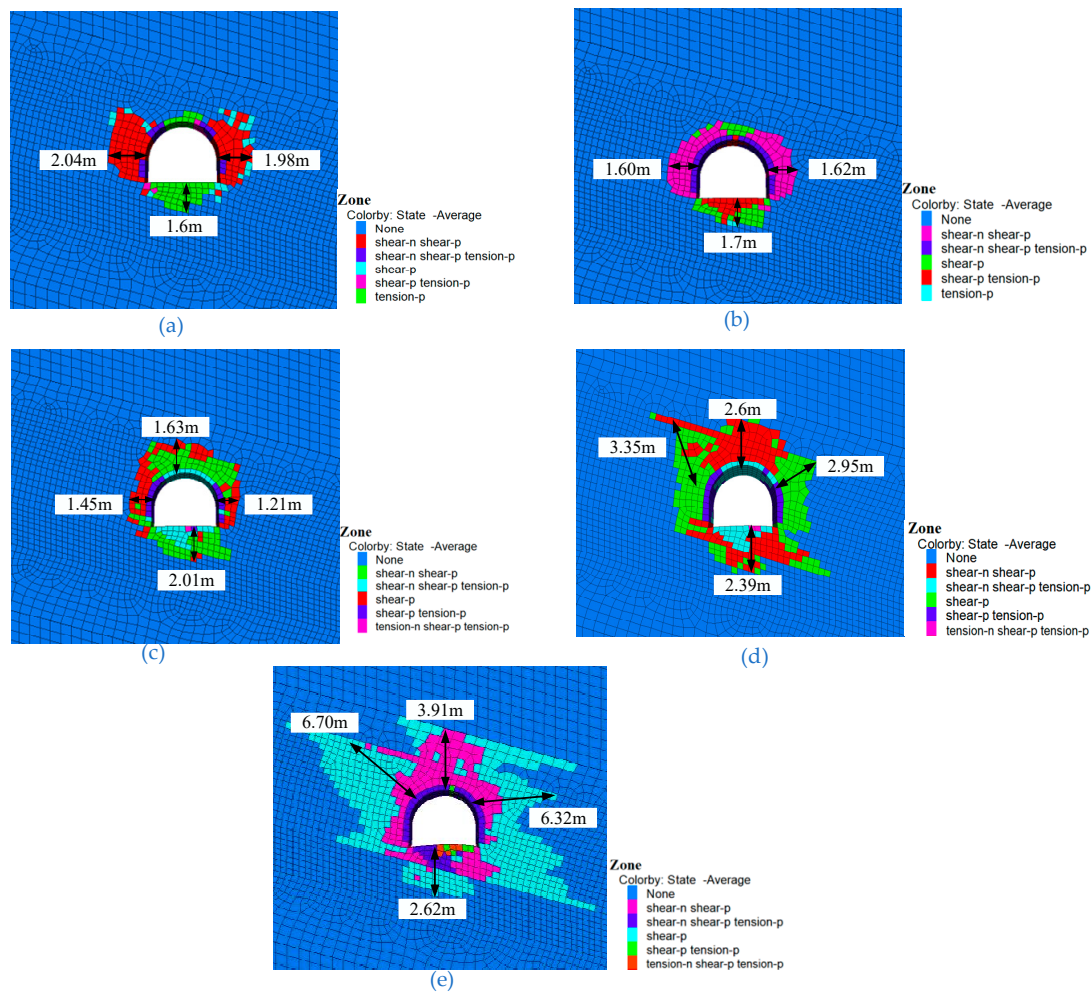


Figure 3. Distribution of the surrounding rock's plastic zone under different tectonic stresses, as follows: (a) $\lambda = 0.5$; (b) $\lambda = 1.0$; (c) $\lambda = 1.5$; (d) $\lambda = 2.0$; and (e) $\lambda = 2.5$.

From the numerical inversion results in Figure 3, it can be seen that the tectonic stress magnitude had an obvious influence on the deformation of the rock surrounding the roadway. The range of the plastic zone around the roadway increased as the lateral pressure coefficient (λ) increased, which indicates that tectonic stress had a significantly destructive effect on the roadway studied. Furthermore, the roof and floor plastic zones were dominated by tension damage, and the plastic zone of the ribs was dominated by shear damage. The rock layer restricted the expansion of the plastic zone and may have caused asymmetric damage to the rock surrounding the roadway, depending on the physical and mechanical properties of the coal rock layer, which was specifically analyzed as outlined in the following paragraphs.

When $\lambda = 0.5$, the plastic zone of the surrounding rock was in a “butterfly” shape; the yielding mode of the surrounding rock of the roof and floor was mainly tensile yielding; the yielding mode of the surrounding rock of the ribs was mainly shear yielding (mostly concentrated in the shoulder, ribs, and floor of the roadway); the plastic zone of the surrounding rock did not extend to the sandy mudstone layer, above the B7 coal seam; the plastic zones of the roof and floor were approximately 0.50 m and 1.60 m, respectively; and the plastic zones of the left and right ribs were approximately 2.04 m and 1.98 m, respectively.

When $\lambda = 1$, the plastic zone of the surrounding rock was an “elliptical” shape and started to develop towards the roof, which made the damage to the roof increase significantly, and the plastic zone of the floor had a tendency to expand deeper along the coal seam, which greatly increased the risk of it leaving the seam. The plastic zones of the roof

and floor were approximately 1.06 m and 1.70 m, respectively, and the plastic zones of the left and right ribs were approximately 1.60 m and 1.62 m, respectively.

When $\lambda = 1.5$, the plastic zone of the rock surrounding the roadway was mainly concentrated in the roof and floor; however, it started to expand to the adjacent rock layers. The range of the plastic zone on the roof and floor was approximately 1.63 m and 2.01 m, respectively, and the range of the plastic zone on the left and right ribs was approximately 1.45 m and 1.21 m, respectively.

When $\lambda = 2.0$, the extent of the plastic zone further increased and showed an extension along the interlayer, which greatly increased the risk of layer separation. The extent of the plastic zone on the roof and floor was approximately 2.6 m and 2.39 m, respectively. The extent of the plastic zone on the left and right shoulders was approximately 3.35 m and 2.95 m, respectively. The plastic zone in both the left and right ribs was mainly concentrated within 1.63 m.

When $\lambda = 2.5$, the plastic zone of the rock surrounding the roadway was still mainly developed on the roof and floor, and the range of the plastic zone of the roof was significantly larger than that of the floor, and the whole sandy mudstone layer above the roof was in the plastic zone—which presents a great risk to the mining of the B6 coal seam. The plastic zones of the roof and floor were approximately 3.91 m and 2.62 m, respectively; the plastic zones of the left and right shoulders were approximately 6.70 m and 6.32 m, respectively; and the plastic zone of both the left and right ribs was mainly concentrated within 5.17 m.

3.4. The Effect of the Tectonic Stress Magnitude on the Deformation Law of the Rock Surrounding the Roadway

In order to study the deformation law of the rock that surrounds weakly cemented roadways, the cross-point method was adopted to determine the influence range of the rock surrounding the roadway. Three measurement lines, each with a length of 11.5 m, were set up in the roadway model. They were laid perpendicular to the roof, floor, and ribs of the roadway (center location). Each line contained 23 measurement points, and the displacement of each point during excavation until stabilization is recorded by the history command in FLAC (this method is also used to study the deformation of different directions and typical cross-layers under the action of tectonic stress).

As shown in Figure 4, the deformation rate of the roof and floor and of the ribs of the surrounding rock and their distance from the roadway all showed three stages of rapid deformation, then gentle deformation, and then stable deformation. After the roadway excavation, the surrounding rock entered the plastic deformation zone, which caused the rapid deformation of the surrounding rock (although this was not disturbed when it was at a certain distance from the roadway but remained in a stable state). With the increase in the lateral pressure coefficient, the maximum displacement of the roof of the roadway increased from 56.1 mm to 191.7 mm, which was an increase of approximately 3.42 times, the maximum displacement of the roadway's roof increased from 56.1 mm to 191.7 mm, which was an increase of approximately 3.42 times; the floor heave increased from 40.8 mm to 170.0 mm, which was an increase of approximately 4.17 times; the maximum displacement of the roadway's left rib increased from 33.8 mm to 161.1 mm, which was an increase of approximately 4.77 times; and the displacement of the roadway's right rib increased from 33.3 mm to 171.1 mm, which was an increase of approximately 5.14 times.

Overall, the deformation of the roof surrounding rock was larger than that of the ribs; the deformation of the shallow part of the roof and floor surrounding rock increased with the increase in the lateral pressure coefficient; and the deformation of the deep part of the roof and floor surrounding rock decreased with the increase in the lateral pressure coefficient. The larger the lateral pressure coefficient, the more unstable the surrounding rock of the roadway was. The maximum displacement of the rock surrounding the weakly cemented roadway, under different lateral pressure coefficients, is shown in Figure 5.

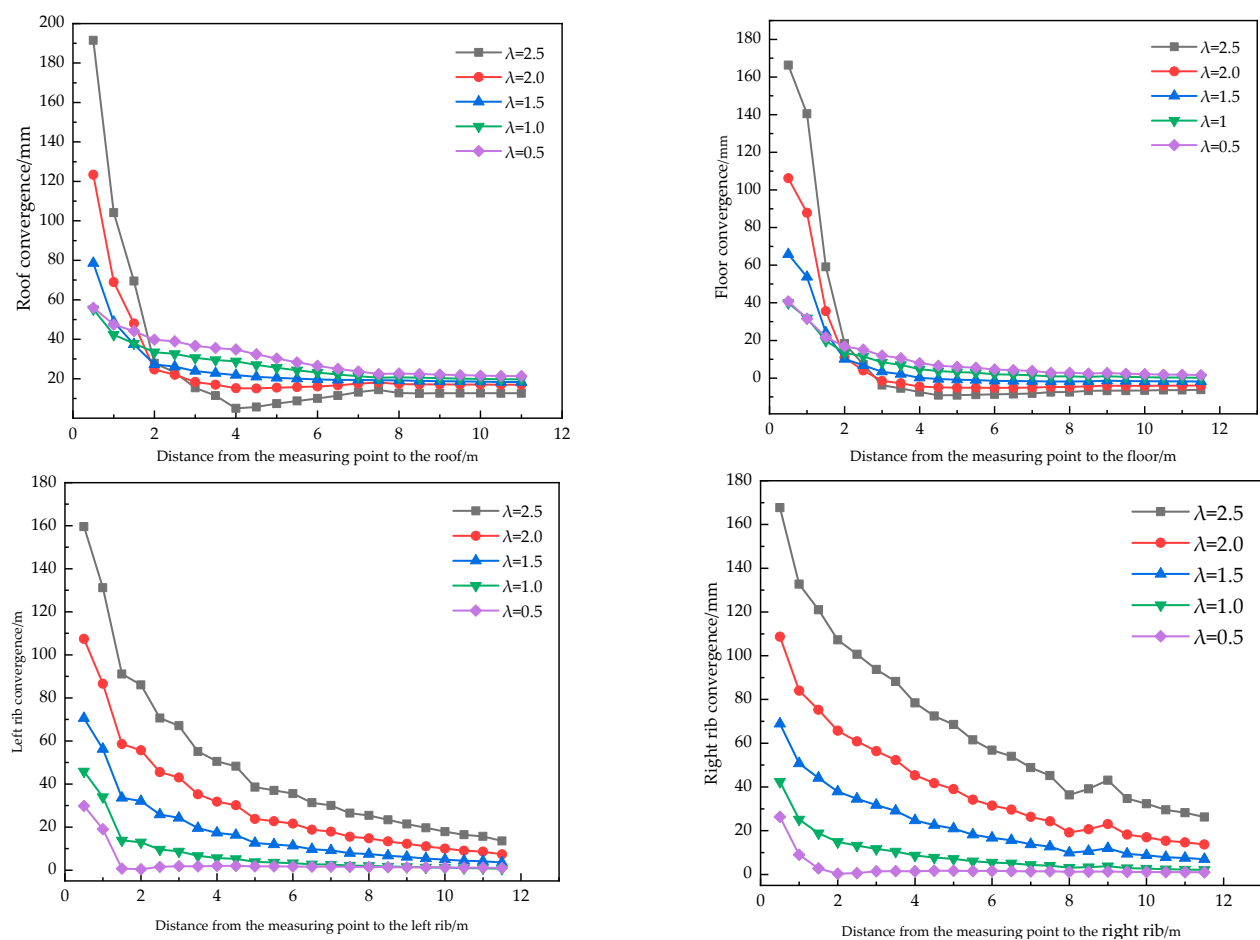


Figure 4. The effect of tectonic stress on the deformation evolution of the roadway and surrounding rock.

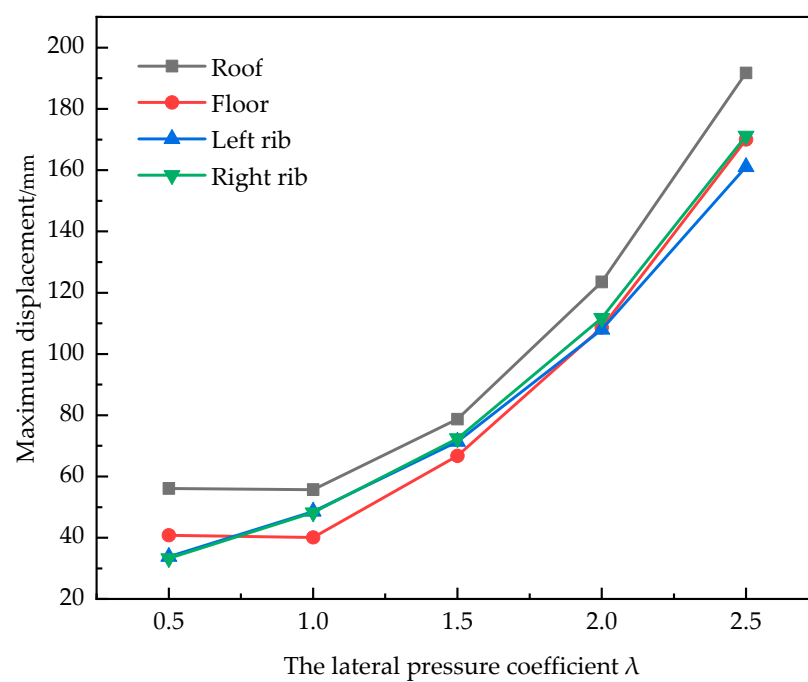


Figure 5. Maximum displacement of the surrounding rock the roadway under the influence of different tectonic stresses.

4. The Influence of the Tectonic Stress Direction on the Deformation of the Rock Surrounding the Roadway

It is known through general engineering practice that the direction of the tectonic stress has an important influence on the stability of weakly cemented roadway enclosures. This section of the paper investigates the mechanism of this influence on the deformation characteristics of the weakly cemented roadway enclosure studied in this work. This was investigated by numerically simulating the maximum horizontal principal stress at different angles to the roadway axis, α .

4.1. Methods

4.1.1. Theoretical Analysis

According to the measurements (see Section 3.1.1) and the knowledge of elastic-plastic mechanics, the original coordinate system related to the direction of ground stress is established, the angle between the maximum horizontal principal stress direction and the roadway axis is set at α , and the three principal stresses are σ_H , σ_v , and σ_h . When α changes, the direction of the roadway axis is used as the reference, and a new coordinate system is established to analyze the results through a stress coordinate conversion (Figure 6). The specific calculation method is shown in Equation (3).

$$\begin{cases} \sigma_{H1} = \sigma_x \sin^2 \alpha + \sigma_y \cos^2 \alpha - 2\tau_{xy} \sin \alpha \cos \alpha \\ \sigma_{h1} = \sigma_x \cos^2 \alpha + \sigma_y \sin^2 \alpha + 2\tau_{xy} \sin \alpha \cos \alpha \\ \tau_{xy1} = \sigma_x \sin \alpha \cos \alpha - \sigma_y \sin \alpha \cos \alpha + \tau_{xy} (\sin^2 \alpha - \cos^2 \alpha) \end{cases} \quad (3)$$

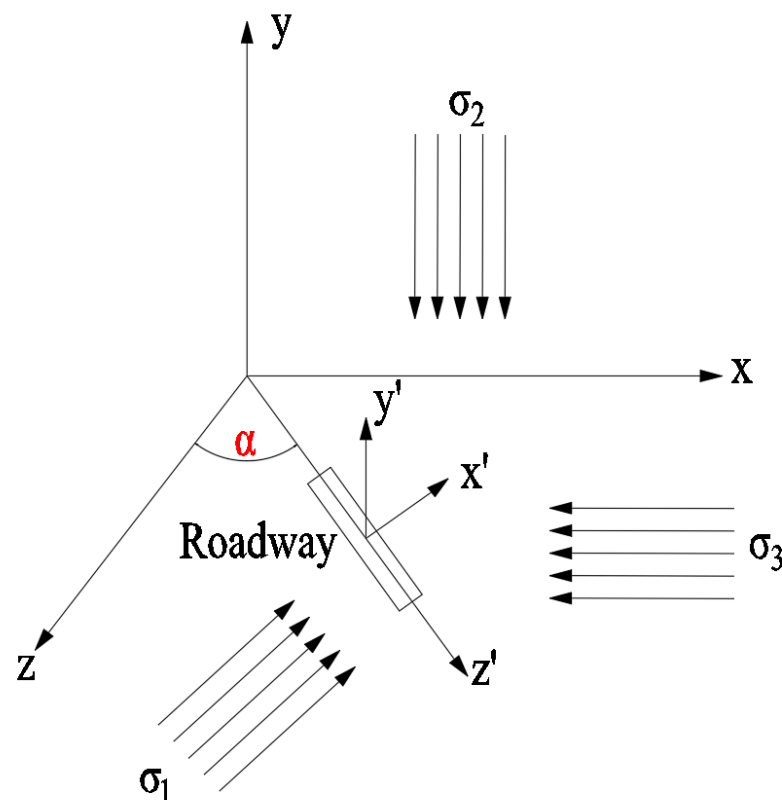


Figure 6. Stress conversion calculation diagram of when the roadway axis and tectonic stress form angle α .

4.1.2. Numerical Model and Simulation Schemes

The numerical model size, boundary conditions, and selected lithological mechanical parameters used in this chapter are consistent with the numerical model in Section 3.2 the effect of the variation of α (i.e., the angle between the roadway and the maximum

horizontal stress) has been studied every 15° from 0° to 90° , except for the initial ground stress scheme, which is shown in Table 3.

Table 3. Simulation scheme of initial ground stress in different directions.

Scheme No.	$\alpha/^\circ$	σ_x	σ_y	σ_z	τ_{xy}	τ_{yz}	τ_{xz}
1	0°	7.34	14.40	7.78	0	0	0
2	15°	7.81	13.93	7.78	1.77	0	0
3	30°	9.11	12.64	7.78	3.06	0	0
4	45°	10.87	10.87	7.78	3.53	0	0
5	60°	12.64	9.11	7.78	3.06	0	0
6	75°	13.93	7.81	7.78	1.77	0	0
7	90°	14.40	7.34	7.78	0	0	0

4.2. Evolution of the Plastic Zone of the Roadway's Surrounding Rock under Different Tectonic Stress Directions

Due to the effects of ground stress and secondary stress, the roadway excavation will make the roadway deformed and damaged. In terms of the stability of the roadway, in order to minimize the stress concentration around the roadway, a reasonable choice of the location and direction of the roadway is an important factor in determining the stability of the roadway. Analysis shows that, in the case of horizontal stress being dominant, the roadway axis and the maximum main stress direction angle are small, and the stress around the roadway is small and relatively uniform. With the increase in the angle, the roadway stress also gradually increased, and the unevenness of the stress was also gradually revealed. Therefore, according to the direction of the maximum horizontal principal stress and taking into account the engineering geological conditions and site construction conditions, comprehensive consideration to choose the best maximum horizontal principal stress and the angle of the roadway axis is one of the effective measures to reduce the roadway deformation damage.

The distribution law of the plastic zone in the rocks surrounding weakly cemented roadways is shown in Figure 7. The shear damage was mainly in the ribs of the roadway, and the mixed shear and tensile damage was mainly in the roof and floor of the roadway. When $0^\circ < \alpha < 45^\circ$, the plastic zone of the surrounding rock decreased with the increase in α , and that the shape of the plastic zone essentially remained the same; the plastic zone of the ribs and shoulders of the roadway was seriously developed; the plastic zone of the surrounding rock of the ribs was larger than the plastic zone of the roof and floor; and the plastic zone of the floor showed a decreasing trend. When $45^\circ < \alpha < 90^\circ$, the plastic zone of the surrounding rock of the roadway expanded to the roof and floor; the plastic zone of the ribs gradually decreased; the plastic zone of the surrounding rock of the roof and floor was larger than that of the ribs; and the plastic zone of the floor developed along the direction of the coal seam, to depth.

4.3. The Influence Law of the Tectonic Stress Direction on the Deformation of the Rock Surrounding Weakly Cemented Roadways

From the numerical simulation results of the surrounding rocks' deformation, as shown in Figure 8, the damage degree of the roof, floor, and ribs of the roadway was different under the different directions of tectonic stress. Among them, the amount of floor heave on the roadway had no obvious difference and was more stable under the action of tectonic stress in different directions, which indicates that when the roadway is supported, controlling the floor heave deformation is an inevitable requirement to ensure the stability of the roadway. With an increase in the angle from approximately 15° to 90° , the roof and floor plate deformation characteristics and the displacement of the roof and floor of the roadway gradually increased. The analysis also showed that the roof was disturbed to a greater extent than the floor, which was related to the fact that the roadway was in the coal seam and that the thickness of the coal seam was larger than that of the floor. To a

certain extent, this also indicates that the lithological structure of the roadway is crucial to its stability. Because of the deformation characteristics of the floor after the increase in the angle, the roof of the roadway gradually sank in, which increased the deformation characteristics of the ribs. Furthermore, the displacement of the left rib gradually increased with the increase in the angle, and the right rib roadway showed the same trend.

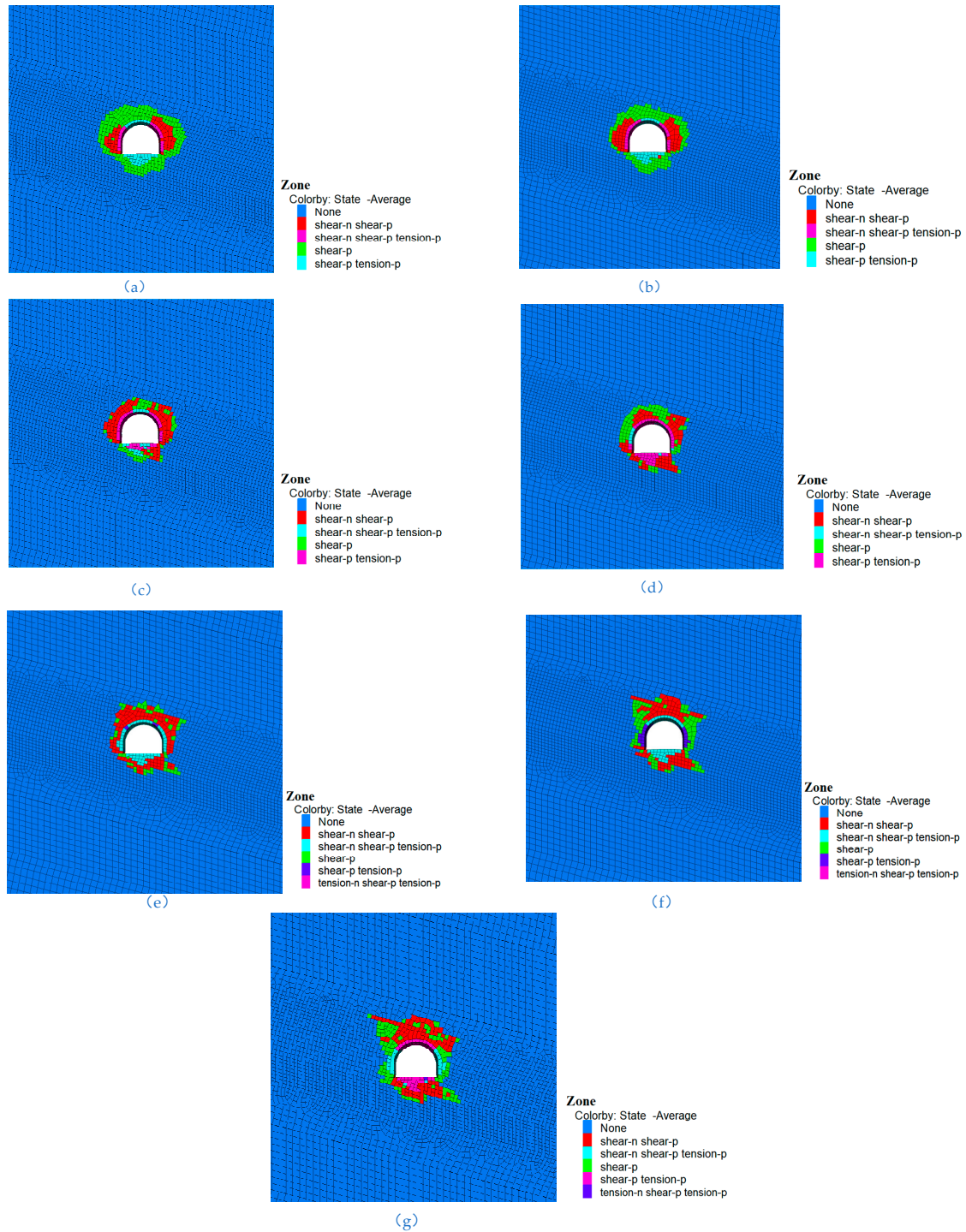


Figure 7. Distribution law of the surrounding rock's plastic zone under different tectonic stress directions, as follows: (a) $\alpha = 0^\circ$; (b) $\alpha = 15^\circ$; (c) $\alpha = 30^\circ$; (d) $\alpha = 45^\circ$; (e) $\alpha = 60^\circ$; (f) $\alpha = 75^\circ$; and (g) $\alpha = 90^\circ$.

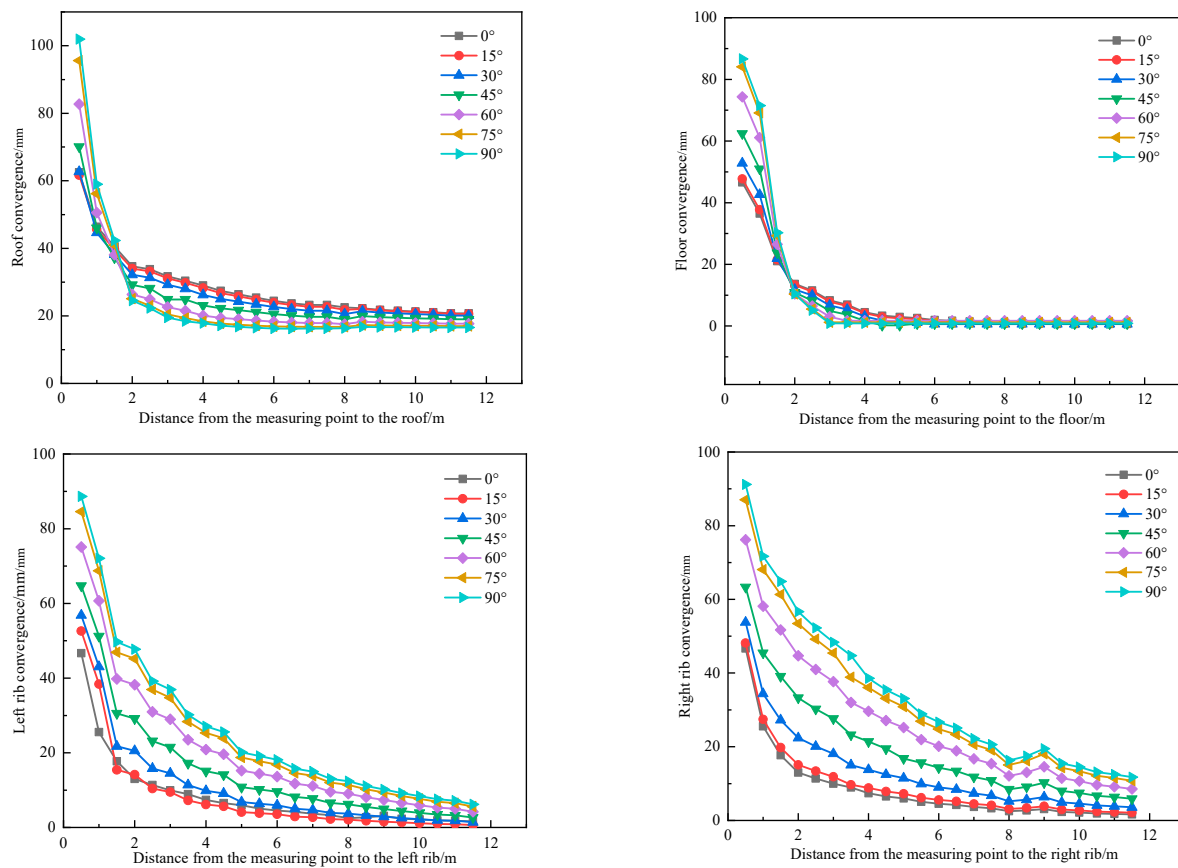


Figure 8. Evolutionary law of deformation of rocks that surround the roadway, changing with different angles.

5. The Influence of the Typical Cross-Layer Roadway on the Deformation of the Rocks That Surround the Roadway

In the process of underground roadway excavations, the different physical and mechanical properties of the strata are usually exposed; the deformation law is still unclear because the bearing structure of the roadway's perimeter rock throughout its layers is of a different medium. The numerical model dimensions, boundary conditions, and selected lithological mechanical parameters used in this chapter are consistent with the numerical model in Section 3.2. The difference is that the location of the roadway arrangement is different. Based on the results of the field stress test, a vertical stress of 7.78 MPa and a horizontal stress of 1.85 transverse pressure coefficient were applied. By studying three typical through-layer roadways, as shown in Figure 9, the deformation mechanism of a weakly cemented cross-layer roadway envelope under tectonic stress was studied by analyzing the plastic zone of the roadway and the deformation characteristics of the surrounding rock.

5.1. Analysis of Vertical Stress Evolution in a Typical Cross-Layer Roadway

In the three typical cross-layer roadways, the proportion of rock and coal gradually increased, and the roadway mainly penetrated the mudstone layer and the coal layer. From the analysis of the different typical cross-layer roadways of vertical stress (Figure 10), the following results are obtained: After the excavation of the roadway, the stress reduction area appeared in a certain range of the roof and floor, and a stress concentration area appeared in the ribs. In the first typical cross-layer roadway, its ribs were generally in symmetry, and the stress concentration area was comparable; however, the stress concentration appeared to be in the left bottom corner, and the maximum stress was 11.8 MPa, which was 1.33 times that of the original rock stress. In the stress concentration of the second type of typical cross-layer roadway, the stress concentration on the left side was obviously higher than that on

the right side, the stress increased on the ribs, the maximum stress was 13.8 MPa—which was 1.54 times that of the original rock stress—and the stress concentration coefficient was approximately 1.15. In the third type of typical cross-layer roadway, the local stress concentration appeared to be in the right bottom corner of the roadway, and the range of the stress concentration in the right rib was obviously higher than that in the left rib, and the stress increased on both sides of the roadway. With an increase in the rock and coal, the stress around the roadway showed a trend of first increasing and then decreasing, and the maximum stress concentration shifted from the bottom corner of the left rib to the bottom corner of the right rib. The stress concentration coefficients of both ribs also showed a trend of first increasing and then decreasing.

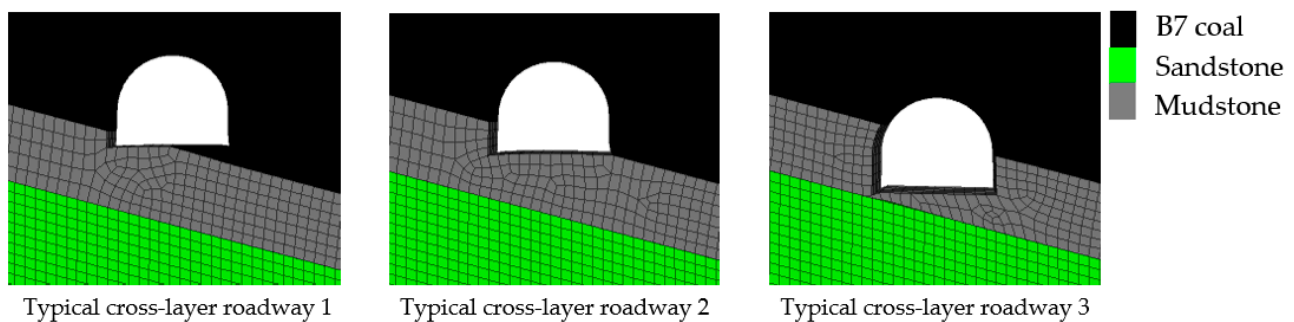


Figure 9. Sketch map of a typical cross-layer roadway.

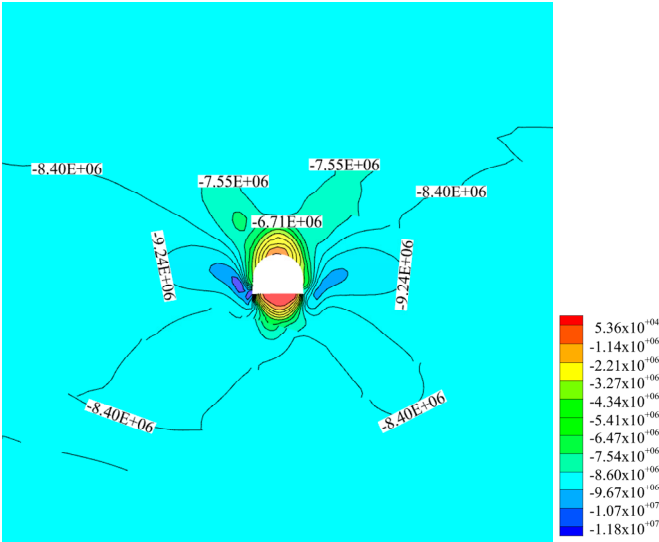
The different lithology will create a significant gap between the stress distribution, deformation, and damage of the rock and coal seams. Due to the low strength of the weakly cemented rock itself, which is similar to the mechanical properties of coal, especially the weakly cemented mudstone in the roof and floor slabs, the change in stress magnitude and gradient in the rocks around the roadway is not very large (including the coal-rock interface).

5.2. Analysis of the Evolution of the Plastic Zone in a Typical Penetration Section

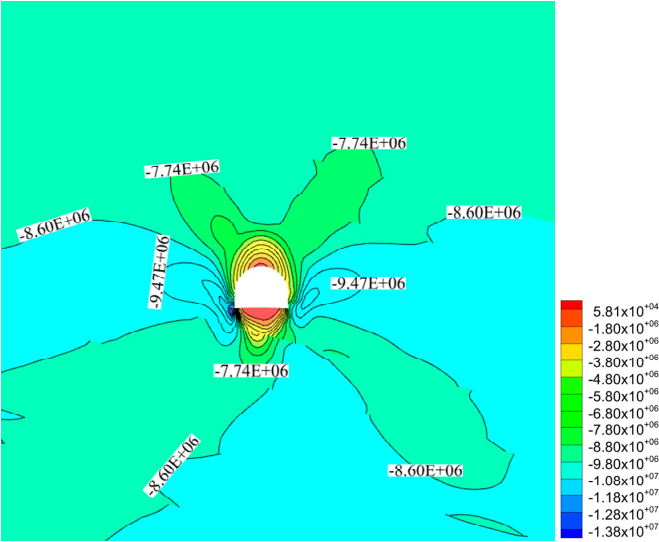
In Figure 11, it can be seen that the plastic zone of the rock surrounding the roadway was 0.59–2.91 m. The plastic zone was mainly concentrated at the roof, at both shoulders, and at the floor, and it showed a trend of decreasing and then increasing from both sides to the bottom angle. The overall shape of the plastic zone was asymmetric because the roadway passes through the mudstone and the coal seam. The average depth of the plastic zone on the left roof was greater than that on the right roof. Therefore, the asymmetric damage to the roadway must be considered when designing the roadway support scheme. In addition, because the roof of the B7 coal seam comprises a sandy mudstone layer and because the rock layer above the sandy mudstone is the B6 coal seam, when designing the anchor cable support, it would be best to secure the cable anchor in the sandstone layer above the B6 coal seam. This was mainly to strengthen the roof and the shoulders; however, the floor should be strengthened according to the actual situation.

5.3. Deformation Evolution Analysis of Surrounding Rocks in a Typical Cross-Layer Roadway

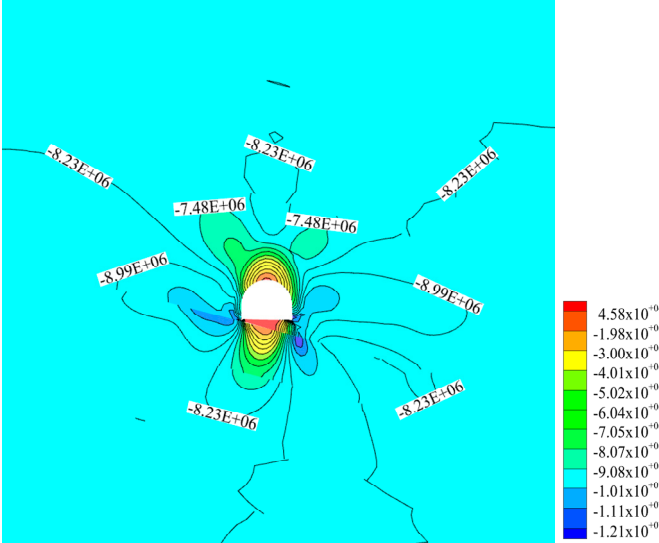
As shown in Figure 12, due to the excavation of the roadway, the surrounding rock entered the plastic deformation zone, which caused the rapid deformation of the surrounding rock. However, the areas that were further away from the roadway were less affected by the mining. From our analysis of the deformation law of the surrounding rocks in three typical cross-layer roadways, with an increase in the rock ratio, the maximum displacement of the roof of the roadway gradually increased, the floor heave of the roadway first decreased and then increased, and the maximum displacement of the left rib first increased and then decreased. Overall, the deformation of the plastic zone around the roadway was concentrated within 3 m, and the deformation around the roadway presented asymmetric deformation.



(a) Typical cross-layer roadway 1



(b) Typical cross-layer roadway 2



(c) Typical cross-layer roadway 3

Figure 10. Z– direction stress cloud map under different typical crossing roadway rocks (unit: Pa).

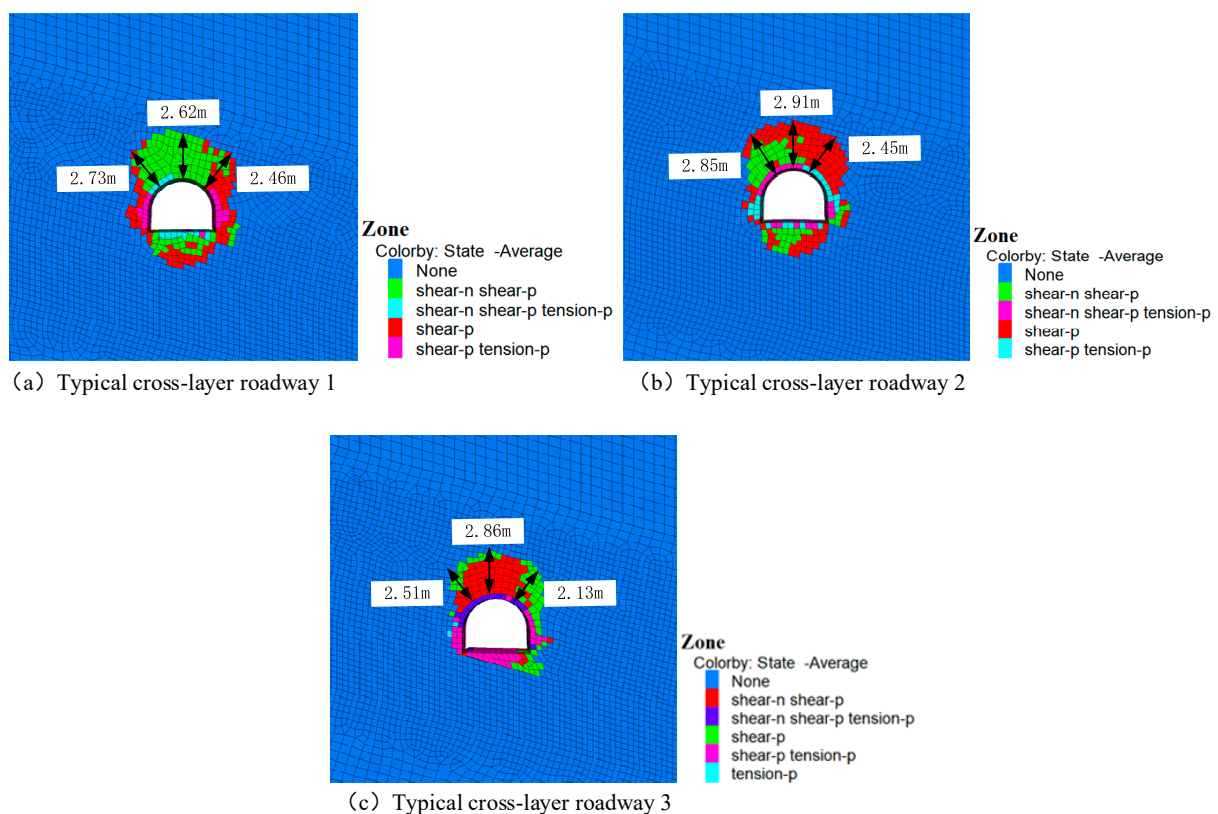


Figure 11. Distribution law of the plastic zone of the surrounding rock, under different typical cross-layer roadways.

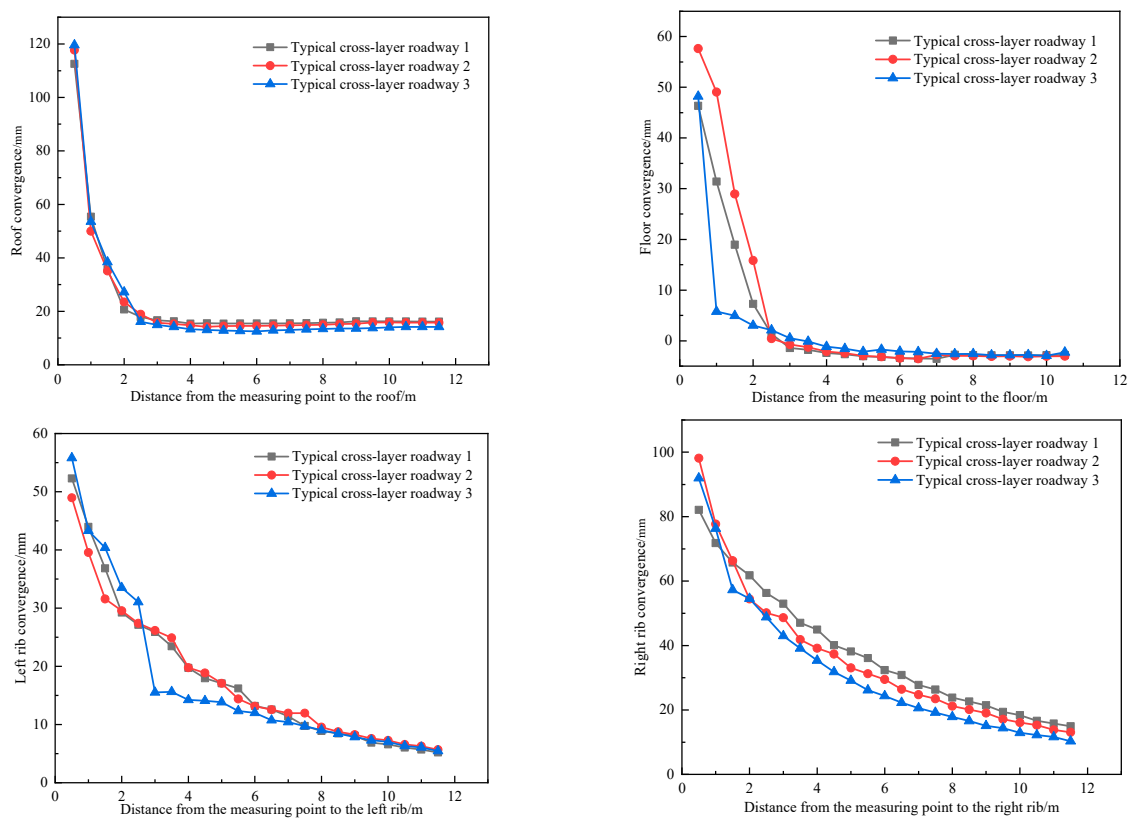


Figure 12. Distribution law of surrounding rock deformation, under different typical cross-layer roadways.

6. Conclusions

In this study, a numerical simulation was carried out in order to study the deformation mechanism of the surrounding rock of a weakly cemented roadway under tectonic stress, the magnitude and direction of the tectonic stress, and the deformation mechanism of typical cross-layer roadways on the surrounding rock of the weakly cemented roadway. After field research, theoretical analysis, and numerical simulation, the following conclusions were drawn:

- (1) Under the action of tectonic stress, the focus should be on strengthening the roof of the roadway support of the slab, which is conducive to the stability of the surrounding rock;
- (2) Roadway deformation and failure for the cases $\lambda < 1.5$ are approximately symmetrically distributed, whereas those for the cases $\lambda > 1.5$ are asymmetric. Roadway deformation, and failure tend to increase in magnitude and extent with increasing λ ;
- (3) Roadway deformation and failure for the cases $\alpha < 45^\circ$ are approximately symmetrically distributed, whereas those for the cases $\alpha > 45$ are asymmetric. Roadway deformation, and failure tend to increase in magnitude and extent with increasing α ;
- (4) Tectonic stress has an important influence on stress redistribution, deformability, and damage in cross-layer roadways;
- (5) When excavating cross-layer roadways under the action of tectonic stress, the concentrated stress around the end of the working face (especially the bottom corner) should be reduced, and the results of the study can provide further reference for the excavation arrangement and support the design of cross-layer roadways.

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