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Study on Asymmetric Deformation Patterns in Layered Soft Rock Tunnels

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Abstract: Layered rock mass is a typical complex rock mass. Owing to its layered structure, its deformation and strength properties exhibit distinct anisotropic characteristics. Taking a deep-excavated railway tunnel as the engineering context, this study investigates the asymmetric deformation laws of layered soft rock tunnels from two perspectives: laboratory tests and numerical simulations. Uniaxial saturated compression tests were conducted to analyze the anisotropic mechanical characteristics of rock bedding planes. This study established a model of layered rock mass tunnel excavation and support. From the perspectives of tunnel peripheral displacement, plastic zone, and maximum principal stress, it reveals the asymmetric deformation characteristics of the surrounding rock under different dip angles of bedding planes. These findings provide valuable insights for the construction of high-stress layered soft rock tunnels.

Keywords: Layered soft rock tunnels; Carboniferous slate; Asymmetric deformation; Anisotropy

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1. Introduction

1.1. Background

Railway tunnel construction often faces the impact of high in-situ stress, high seismic intensity, and complex tectonic stress fields. Beyond these challenges, a common characteristic is traversing stratigraphic formations composed of carbonaceous shale, phyllite, and other layered, weak strata. These formations exhibit poor mechanical properties and low self-stabilizing capacity, leading to issues such as spalling and failure of initial support, as well as distortion and deformation of rigid arches. These issues pose significant challenges to both the construction and operation stages of the tunnel. Existing research has established a fundamental theoretical framework for the deformation mechanisms of layered soft rock, with existing research primarily focusing on lateral pressure issues caused by topography and weak interlayers [1–12]. However, the constitutive behavior of the surrounding rock remains the dominant factor governing the evolution of large deformations. Based on a deep-excavated railway tunnel, this paper studies and analyzes the influence of bedding plane occurrence on the asymmetric deformation laws of layered soft rock tunnels by means of laboratory tests and numerical simulations.

1.2. Project overview

The tunnel is a high-altitude double-track, twin-bore railway tunnel. The portal elevation is approximately 2,735 meters, while the exit elevation is approximately 3,260 meters, presenting an elevation difference of 525 meters. The track spacing is 45 meters, with a maximum burial depth of approximately 670 meters. The surrounding rock is complex and variable in lithology, predominantly consisting of slate with local intercalations of sandstone. The schist exhibits a predominantly microcrystalline mudstone texture with localized sandy structures, exhibiting extremely thin-bedded formations typically less than 1 cm thick. Inter-bedding cohesion is poor, classifying it as weak rock mass. This poses a significant risk of large deformation due to compression during excavation. The tunnel zone traverses strata within joint zones and densely jointed areas, predominantly oriented NE with predominant dip directions of 100° to 150°, generally exhibiting steep dip angles. Joint spacing generally ranges from 0.5 to 2.0 meters, with extensions exceeding 1.0 meter. Most joints are either closed or slightly open, lacking infill and exhibiting relatively straight orientations. Statistical analysis of joint dip directions and dip angles for the Triassic Longwu River Formation is presented in **Figure 1**. In-situ stress testing was conducted across 29 measurement sections within six deep boreholes in the tunnel zone. As shown in **Figure 2**, the maximum horizontal principal stress reached 22.88 MPa, classifying this as a high-to-extremely high in-situ stress zone.

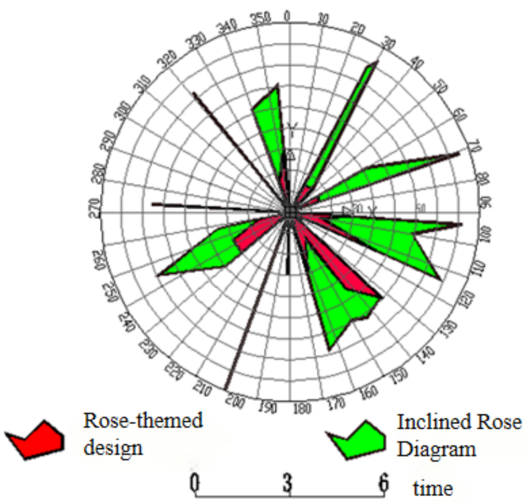


Figure 1. Rose-shaped joint pattern.

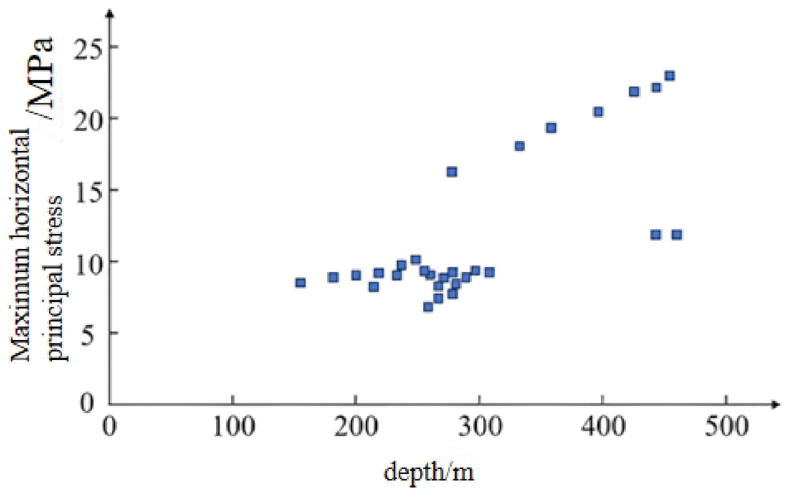


Figure 2. Relationship between maximum horizontal principal stress and tunnel depth.

2. Rock mass mechanical properties

To investigate the mechanical properties of rock blocks with varying bedding plane angles, thin-bedded jointed rock blocks predominantly composed of carbonaceous shale were selected. All specimens were extracted from the same excavation cross-section within the tunnel. Owing to the distinctive thin-bedded sedimentary structure of carbonaceous slate, the sampling success rate was low, and the specimens were not derived from a single block. Carbonaceous slate specimens were drilled at five angles: 0°, 30°, 45°, 60°, and 90°. The specimens were cylindrical in shape, with a diameter of 50 mm and a length of 10 mm, tolerances of ± 0.5 mm, and end-face parallelism of ± 0.02 mm. Uniaxial saturated compressive strength tests were conducted on carbonaceous slate specimens with different bedding plane orientations. The results obtained from these tests are presented in **Figure 3**.

dip	dip-0°	dip-30°	dip-45°	dip-60°	dip-90°
Ultimate compressive strength/MPa	23.12	16.67	9.44	18.87	37.35
Secant Elastic ModulusE50/GPa	23.07	4.98	4.20	4.58	34.52

Figure 3. Mechanical properties of specimens at different inclination angles.

The test results indicate

(1) The ultimate compressive strength and secant modulus of rock specimens obtained from uniaxial compression tests reveal pronounced anisotropic mechanical properties in layered carbonaceous shale. Analysis of failure characteristics across different bedding plane orientations indicates that the weak bedding planes constitute the primary factor influencing the rock mass's anisotropic mechanical behavior. The uniaxial saturated compressive strength and secant modulus of the rock blocks exhibit a U-shaped variation with respect to the bedding plane angle.

(2) When the loading direction is parallel to the bedding plane (bedding plane angle 90°), both the ultimate compressive strength and secant modulus are greater than when the loading direction is perpendicular to the bedding plane (bedding plane angle 0°). At a bedding plane angle of 45°, both ultimate compressive strength and tangent modulus of elasticity attain their minimum values. The uniaxial saturated compressive strength of rock blocks at different angles provides a partial explanation for the occurrence of buckling failure in tunnels through layered soft rock.

3. Study on the physical field characteristics of three-layered soft rock tunnels

3.1. Stratigraphic-structural model and selection of constitutive parameters

The Ubiquitous-Anisotropic model is based on the Mohr-Coulomb constitutive relationship, adhering to the Mohr-Coulomb yield criterion. It incorporates anisotropic constitutive behavior by embedding weak planes oriented in specific directions. The geological formation traversed by the tunnel consists of carbonaceous laminated schist, exhibiting pronounced anisotropic mechanical characteristics. Physical and mechanical parameters of the rock mass were determined in accordance with the Technical Specification for Railway Tunnels in Compressible Surrounding Rock. A ubiquitous jointed constitutive model was employed to simulate the excavation of a layered soft rock tunnel, with the parameters used for simulation shown in **Table 1**.

Table 1. Constitutive parameters

Constitutive parameters	Unit	Parameter range
dip	°	0–90
dip-direction	°	90
joint-cohesion	MPa	0.6
joint-friction	°	25
joint-tension	GPa	0.18
young-plane	GPa	1.2
young-normal	GPa	0.5
poisson-plane	/	0.4
poisson-normal	/	0.2
density	kg/m^3	2000

The computational model employs the actual cross-sectional dimensions of the tunnel, as illustrated in **Figure 4**. Support parameters are classified as Grade V, with the tunnel buried at a depth of 600 meters. The fundamental assumptions for the geological-structural model are as follows:

(1) Both stress and strain in the strata and support parameters remain within the elastic-plastic range

(2) The influence of tunnel excavation on rock mechanical parameters is disregarded

(3) The effects of groundwater seepage are not considered

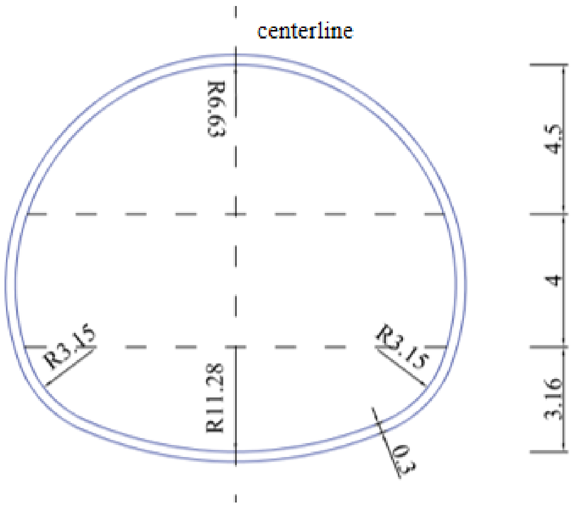
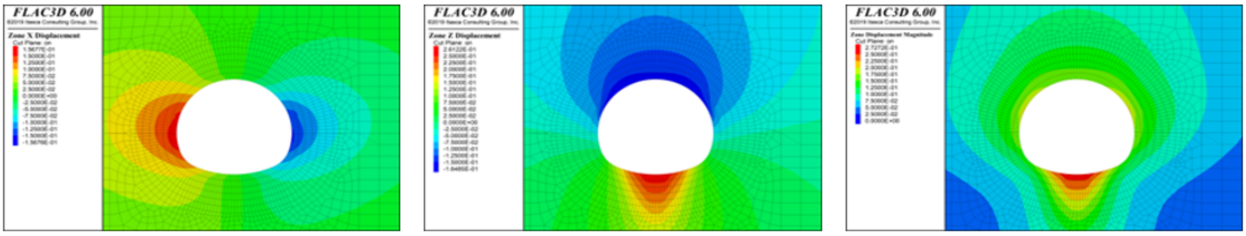


Figure 4. Tunnel cross-section diagram.

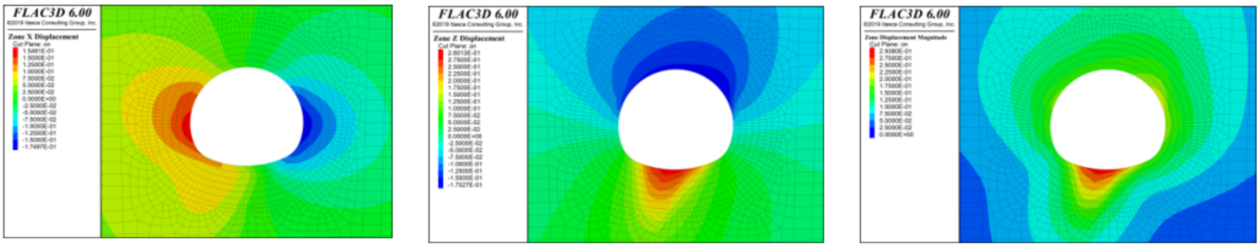
3.2. Perforation displacement

Following completion of the tunnel excavation, horizontal displacement, vertical displacement, and combined displacement contour plots under different inclination conditions for the same stratigraphic plane inclination were selected at the mid-section (Y = 60 m), as shown in **Figures 5** to **11**.



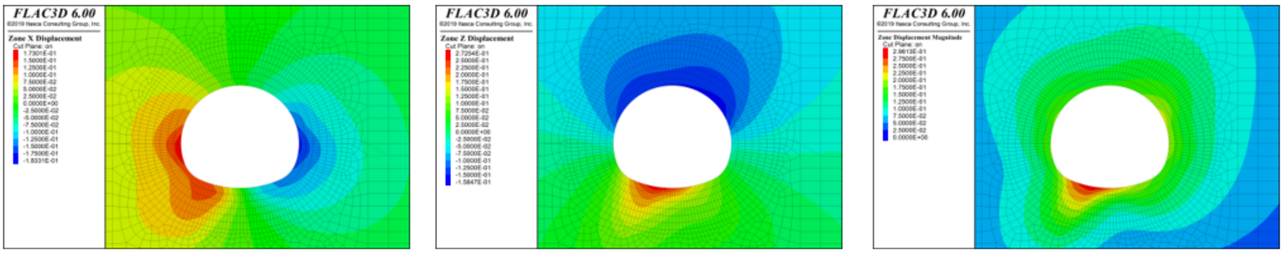
(a) Horizontal displacement (b) Vertical displacement (c) Resultant displacement

Figure 5. dip-0°.



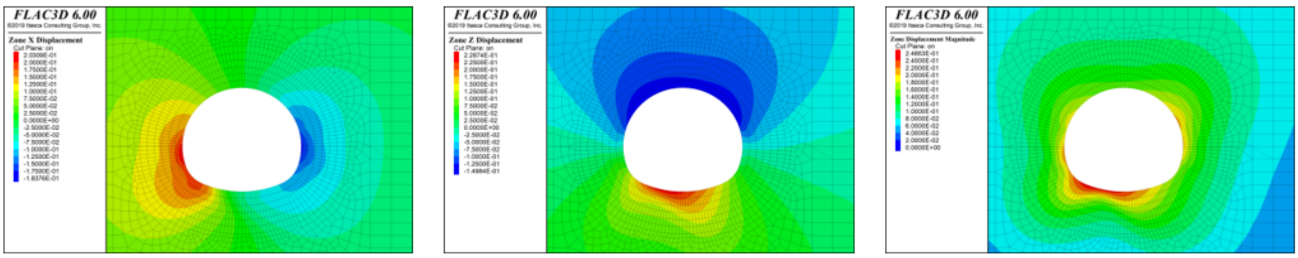
(a) Horizontal displacement (b) Vertical displacement (c) Resultant displacement

Figure 6. dip-15°.



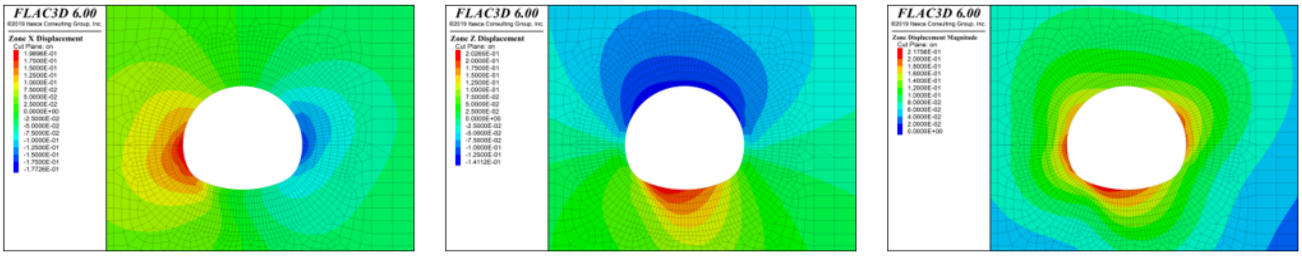
(a) Horizontal displacement (b) Vertical displacement (c) Resultant displacement

Figure 7. dip-30°.



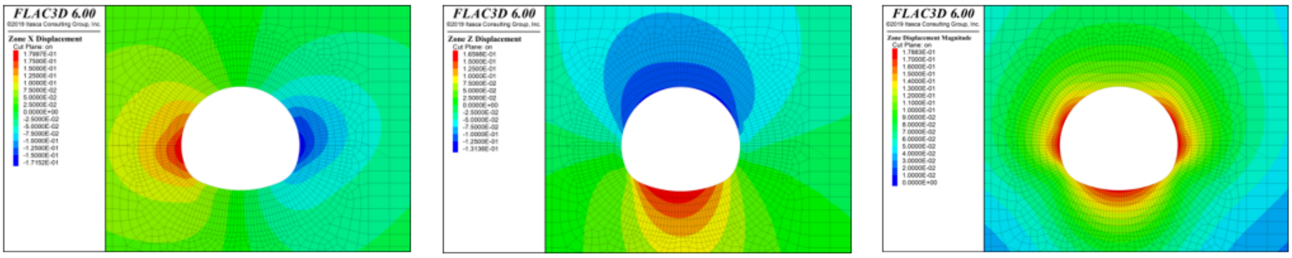
(a) Horizontal displacement (b) Vertical displacement (c) Resultant displacement

Figure 8. dip-45°.



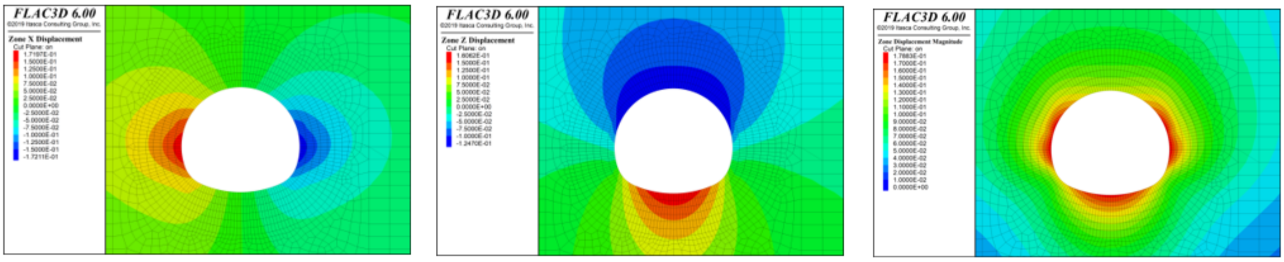
(a) Horizontal displacement (b) Vertical displacement (c) Resultant displacement

Figure 9. dip-60°.



(a) Horizontal displacement (b) Vertical displacement (c) Resultant displacement

Figure 10. dip-75°.



(a) Horizontal displacement (b) Vertical displacement (c) Resultant displacement

Figure 11. dip-90°.

From the deformation characteristics observed around the rock cavities at different stratigraphic dip angles (see **Table 2**), it can be seen that:

(1) The deformation characteristics of the tunnel perimeter in layered soft rock tunnels vary with the dip angle of the bedding plane. Except for dip angles of 0° and 90°, both the horizontal and vertical displacements of the tunnel perimeter differ from those in homogeneous rock masses, exhibiting distinct asymmetric features. The location of maximum deformation in the surrounding rock gradually shifts from the invert and crown towards the left and right sidewalls, with the primary deformation zone changing as the position deviates from the normal to the bedding plane.

(2) In layered soft rock tunnels, the vertical relative convergence value decreases with increasing dip angle, while the horizontal relative convergence value first increases then decreases. When the dip angle exceeds 45°, the horizontal relative convergence value around the tunnel exceeds the vertical relative convergence value, and the dominant displacement direction shifts from vertical to horizontal deformation.

It is evident that the weak-zone effect within layered rock formations exerts a significant influence on the deformation characteristics of tunnel surrounding rock, constituting the primary cause of asymmetric displacement patterns around the tunnel borehole. Consequently, during the construction of tunnels through layered soft rock, support measures must be specifically designed to address the distinct orientations of different bedding planes.

Table 2. Deformation displacement values around the tunnel

Dip	Vaulted ceiling sagging /mm	Cambered arch /mm	Maximum horizontal displacement on the left side /mm	Maximum horizontal displacement on the right /mm	Maximum deformation /mm
0°	-164.8	261.2	156.7	-156.7	272.7
15°	-170.2	280.2	154.8	-174.9	293.8
30°	-158.4	272.5	173.0	-183.3	296.1
45°	-149.8	228.7	203.0	-183.7	246.6
60°	-141.1	202.6	198.9	-177.2	217.5
75°	-131.3	165.9	179.9	-171.1	185.9
90°	-124.7	160.6	171.9	-172.1	178.8

3.3. Distribution of plastic zones

The stability of the rock mass-support system is governed by the shallow rock mass (loose zone, plastic zone). The presence and distribution characteristics of the plastic zone exert a significant influence on the load-bearing properties of the support structure. With a lateral pressure coefficient of 1.2 and a dip of 90°, the distribution of the plastic zone under different bedding plane inclinations is illustrated in **Figure 12**.

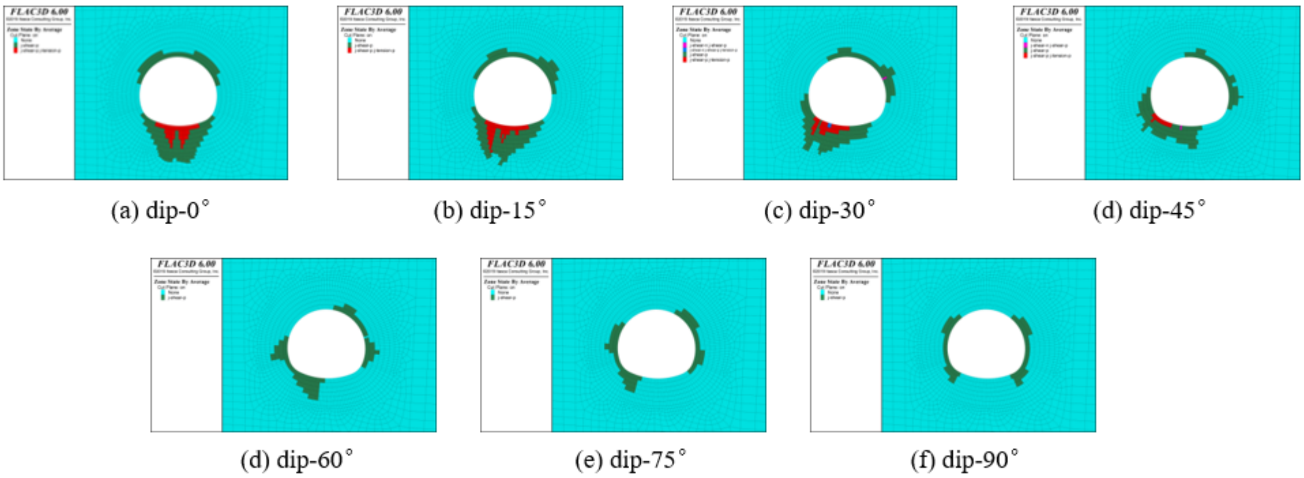


Figure 12. Plastic zone distribution.

From the distribution of the plastic zone at different inclination angles (see **Table 3**), it can be seen that:

(1) The maximum depth of plastic zones at the crown and base of the arch diminishes as the dip angle of bedding planes increases. Within the 0° to 30° dip range, plastic zones exhibit greater depth at the crown and invert positions, with the invert region displaying deeper plastic zones than the crown area. Overall distribution indicates plastic zones predominantly occur along the normal direction of bedding planes.

(2) The primary distribution of the plastic zone within the surrounding rock is significantly influenced by the dip angle of the strata. As the dip angle of the bedding plane varies from 0° to 90°, the main distribution area of the plastic zone shifts from the crown and invert towards the abutments and side

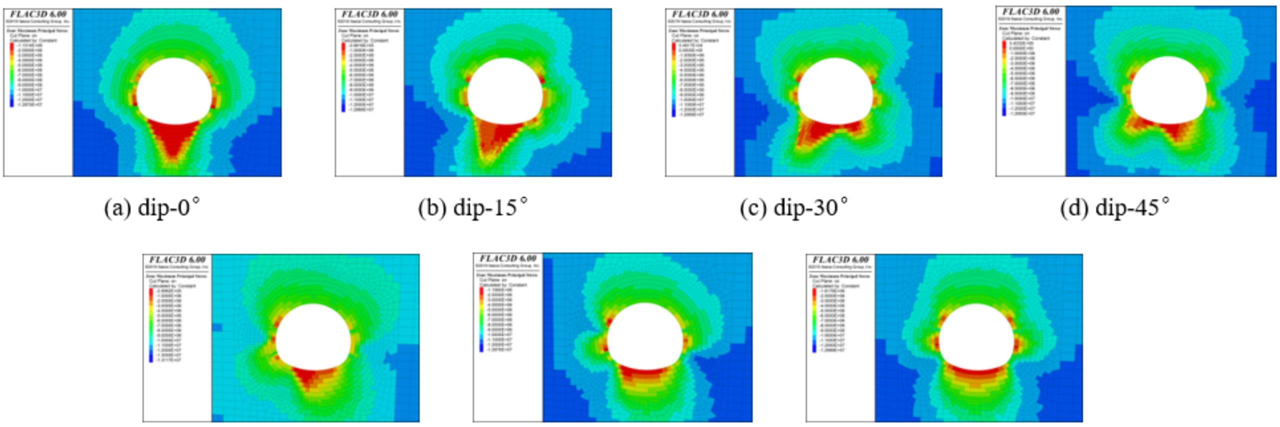
walls. This pattern parallels the evolution of the displacement field around the tunnel, transitioning from predominantly vertical deformation to predominantly horizontal deformation.

Table 3. Maximum depth of plastic zone at different inclination angles and positions

Dip	Location of the plastic zone			
	Tunnel crown /m	Tunnel invert /m	Tunnel abutment /m	Tunnel sidewall /m
0°	1.6	5.6	1.6	0.8
15°	1.6	5.6	2.4	0.8
30°	1.6	4.8	0.8	1.6
45°	1.6	4	0.8	2.4
60°	0.8	4	1.6	3.2
75°	0.8	3.2	1.6	1.6
90°	0	0	1.6	0.8

3.4. Analysis of maximum principal stress

Following tunnel excavation, the original stress equilibrium state of the surrounding rock is disrupted, leading to stress redistribution within the adjacent rock mass. Consequently, both the magnitude and direction of the maximum principal stress undergo alteration. Analyzing the influence of bedding plane weakness from the perspective of maximum principal stress, the stress distribution map for a bedding plane inclination with a lateral pressure coefficient of 1.2 and varying bedding plane dips is illustrated in **Figure 13**.



(a) dip-0° (b) dip-15° (c) dip-30° (d) dip-45°

(d) dip-60° (e) dip-75° (f) dip-90°

Figure 13. Contour map of maximum principal stress.

The calculation results (see **Table 4**) indicate that:

(1) The distribution characteristics of the maximum principal stress in the surrounding rock exhibit deflection with changes in the dip angle of the bedding plane, displaying an asymmetric pattern similar to the distribution patterns of tunnel perimeter displacement and plastic zones. The maximum principal stress in the surrounding rock around the tunnel is predominantly compressive. Within the zones of low absolute values for maximum principal stress, deformation in the surrounding rock is significant, and the direction of deflection of the maximum principal stress aligns with the normal direction of the bedding plane.

(2) As the dip angle of the bedding plane increases, the minimum absolute value of the maximum principal

stress exhibits a U-shaped variation pattern. Within zones of low maximum principal stress, significant deformation occurs in the surrounding rock. The maximum displacement around the tunnel first increases and then decreases, displaying identical deformation characteristics. This indicates a close correlation between rock mass deformation and the maximum principal stress.

Table 4. Maximum principal stress at different stratification surface inclinations

Dip	0°	15°	30°	45°	60°	75°	90°
Minimum absolute value of the maximum principal stress/MPa	-1.13	-0.268	0.054	0.342	-0.289	-1.15	-1.81

4. Conclusion

This study is based on laboratory uniaxial saturated compression tests on carbonaceous slate with different dip angles. By comprehensively considering rock mechanical properties and numerical simulation analysis, it investigates the influence of bedding plane occurrence on the laws of large deformation in layered soft rock tunnels from three dimensions: tunnel peripheral displacement, plastic zone distribution, and maximum principal stress. Conclusions are as follows.

(1) The distribution laws of tunnel peripheral displacement and plastic zones in layered soft rock tunnels are significantly affected by bedding plane occurrence. Compared with homogeneous rock masses, they exhibit asymmetric and non-uniform deformation characteristics. Specifically, during the transition from horizontal layered rock strata to steeply dipping layered rock strata, the deformation mode changes from vertical deformation to horizontal deformation.

(2) With the increase of bedding plane dip angle, the minimum value of the absolute value of the maximum principal stress shows a "U"-shaped variation trend. The maximum peripheral displacement of the tunnel first increases and then decreases. The low-value areas of the maximum principal stress and the locations of maximum deformation in the surrounding rock around the tunnel exhibit the same deformation characteristics, indicating a close relationship between the deformation of the surrounding rock and the maximum principal stress.

(3) Given that the deformation characteristics of layered soft rock tunnels are significantly affected by bedding plane occurrence and exhibit obvious asymmetric features, specific designed support measures should be adopted for different bedding plane occurrences in actual tunnel engineering construction. For areas with large deformation (in the normal direction of bedding planes), measures such as increasing the number of bolts and applying anchor cables can be used to reinforce the surrounding rock to restrict its deformation.

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Disclosure statement

The authors declare no conflict of interest.

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