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ORIGINAL PAPER

Numerical Simulation Study on the Anchorage Mechanism of Yield Supporting in Deep Tunnel

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Abstract In order to study the influence of yield supporting on the zonal disintegration of tunnel surrounding rock under layered lithology in deep tunnel and its anchoring mechanism. Through the analysis of the rock strain/displacement around the tunnel, it's clear that the combined support form of the rigid lining and the yielding anchor bolt has the best supporting affection in the four supporting forms, which can effectively suppress the zonal disintegration of the deep surrounding rock. At the same time, stress transfer is realized and the zonal disintegration trend of surrounding rock is weakened. Through the analysis of the internal force calculation results of the support structure, it shows that the combined yield supporting structure plays a supporting and anchoring role to the surrounding rock, and realizes the stress distribution, so that the stress field around the tunnel is more uniform. At the same time, the yielding anchor bolt can prevent the failure of the bolt in the deformation because of premature yielding, thus improving the supporting strength of the supporting structure. The research shows that the new combined support structure with rigid lining and pressure/yielding anchor is of great significance for inhibiting/suppressing zonal disintegration of deep rock tunnel.

Keywords Deep tunnel · Numerical simulation · Yield supporting · Zonal disintegration · Anchorage mechanism

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1 Introduction

In recent years, as the depth of the underground works increased, many new engineering geological phenomena have appeared in deep rock mass, such as rock burst, large deformation of the surrounding rock and the zonal disintegration. The study on the support of zonal disintegration of deep rock mass has become the focus of academic research.

For the deep rock mass zonal disintegration phenomenon, the zonal disintegration was found firstly by Shemyakin et al. (1986a, b; 1987) in Taymyrsky mining. And others researches have mostly used indoor physical model test methods (Qian 2004, 2008; Li et al. 2006; Qian and Li 2008; Gu et al. 2008). With the maturity of numerical software technology, lots of scholars have simulated the zonal disintegration phenomenon by numerical calculation software in recent years. Qian et al. (2009) have simulated the zonal disintegration phenomenon of the diversion tunnel of Jinping II level hydropower station, and had gotten the zonal disintegration area of the tunnel surrounding rock. Li et al. (2011) has used the FISH language of FLAC^{3D} to develop the simulated zonal disintegration calculation program, and used the program to simulate the zonal disintegration morphology in deep tunnel, which was in good agreement with the field observations. According to the non-Euclidean geometric model, Zhou et al. (2012) has obtained the damage variable of the surrounding rock of the deep circular tunnel and got the distribution law of the deep damaged surrounding rock fracture and non-fracture zone.

Due to the high stress state, the deformation and failure of the surrounding rock of deep tunnels have obvious nonlinear characteristics, and the traditional supporting structures often fail due to the high stress of surrounding rock. Someone (Lian and Wang 2013; Li and Zhu 2012; Lian et al. 2008a, b; Zhu et al. 2015; Zhang et al. 2008) have carried out numerical simulation study on the yielding structure supporting for the deformation of surrounding rock of deep tunnel, and study the action mechanism of the yielding structure.

In order to study the influence and anchorage mechanism of the yielding supporting structure of deep tunnel on the zonal disintegration of surrounding rock, a numerical model is established by using MIDAS-GTS numerical software. By comparing the numerical model failure cloud map, surrounding rock displacement of the hole, strain calculation results and calculation results of internal force of support structure under four different supporting conditions, the mechanical mechanism of the combined yielding supporting structure and surrounding rock is analyzed, and the anchoring mechanism of the yielding structure of deep tunnel is deeply analyzed.

2 The Establishment of a Numerical Model

2.1 Calculation Model and Boundary Condition

Numerical calculation model: In order to compare with the physical test, the numerical calculation model of deep tunnel used two kinds of rock parameters to hierarchically lay entity unit to simulate stratified lithological surrounding rock, with the total of 11 layers. The tunnel was simulated using the straight wall vaulted chamber, which was widely used in underground engineering. The chamber size was as follows: the width of the tunnel section was 200 mm, the height of the straight wall was 100 mm, and the vault height was 100 mm. According to the Saint-Venant principle, the damage range of the tunnel surrounding rock was between 3 and 5 times of the radius of the tunnel. At the same time, in order to save the calculation time, the size of the numerical calculation model of each supporting condition was X × Y × Z: 2500 mm × 2500 mm × 2500 mm. X was the axis direction of the vertical chamber, Y was the axis direction of the chamber, and Z was the depth direction. The total unit number of models was 143922, and the total number of nodes was 158916. The calculation model is shown in Fig. 1.

Numerical boundary condition: According to the previous studies on the zonal disintegration of the surrounding rock of deep tunnels, the formation of the zonal disintegration is formed due to the large axial pressure and small lateral pressure of the rock mass under the effect of tectonic stress. Therefore, the normal constraint of non-rotation was set on the bottom, the right and the back of the calculation model. At the same time, the normal uniform load was applied on the left, top and front of the model to simulate the stress field of the surrounding rock of the deep tunnel. Stress loading conditions were as follows: The upper load was calculated according to the self-

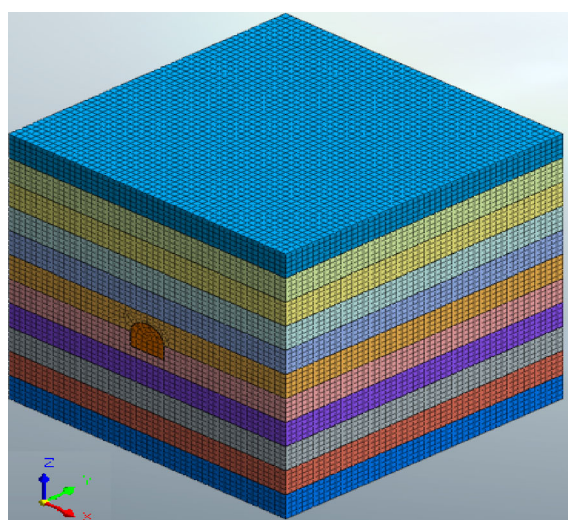


Fig. 1 Calculation model and grid division

weight load γh (h is the burial depth of the tunnel), $\sigma_z = \gamma h / C_\sigma = 1$ MPa. The left load was calculated according to the lateral stress coefficient of 1.5, $\sigma_x = \lambda \times \gamma h / C_\sigma = 1.5$ MPa. The front (axial plane) load was calculated by 2 times the material compressive strength $\sigma_y = 2f_c = 2.5$ MPa. The specific boundary conditions and loading application conditions are shown in Figs. 2 and 3.

2.2 The Selection of Constitutive Model

The accuracy of numerical calculation depends largely on the selection of constitutive model. The interaction relationship between deep rock mass and support structure is simulated mostly by elastoplastic constitutive model in numerical calculation. The failure criterion of tunnel surrounding rock and grouting material adopts the Drucker–Prager (D–P) failure criterion. Although the traditional Mohr–Coulomb (C–M) criterion can reflect the essence of compressive shear failure of rock and soil materials, and it is widely used, this criterion does not take into account the influence of intermediate stress and cannot explain the phenomenon of yield and destruction under the hydrostatic pressure of rock and soil materials. The D–P criterion takes into account the intermediate principal stress, considers the effect of hydrostatic pressure and overcomes the main weakness of the C–M criterion. At the same time, it has been widely used in the numerical calculation of geotechnical engineering at home and abroad because of its smooth failure surface. The expression is:

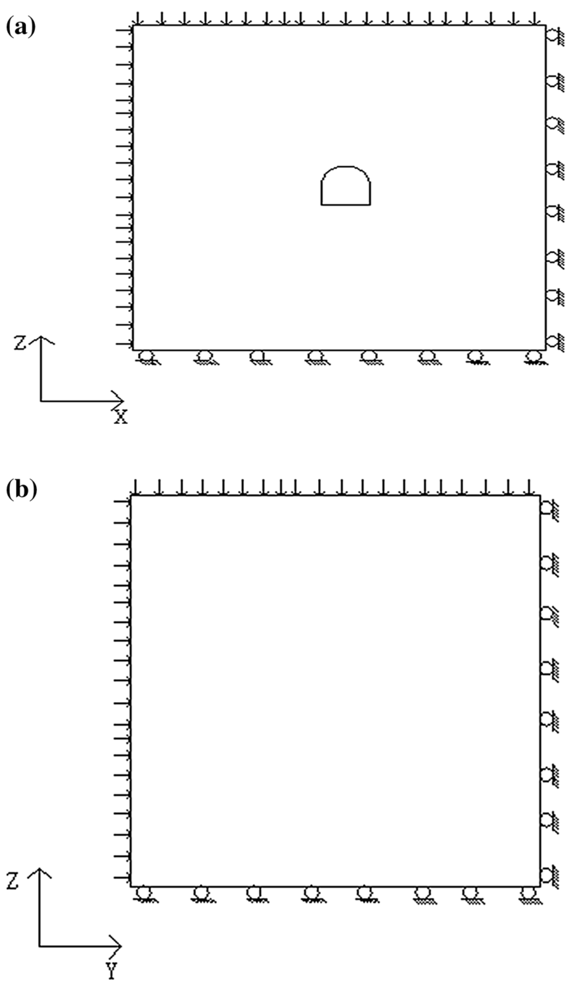


Fig. 2 The Boundary conditions and loading conditions for the simulation model. **a** Z and X direction. **b** Z and Y direction

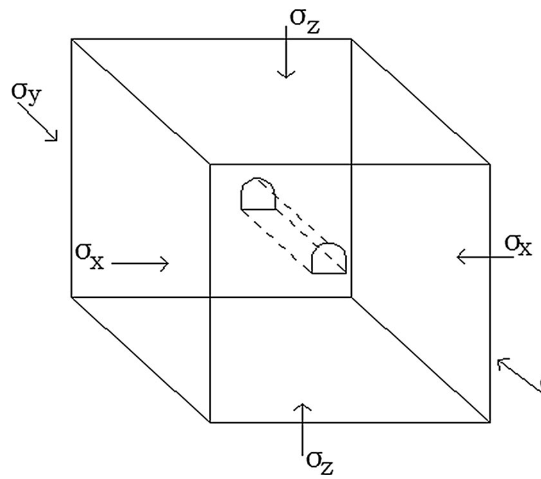


Fig. 3 Stress field loading sketch map of surrounding rock of straight wall arch chamber

$$f\left(I_1, \sqrt{J_2}\right) = \sqrt{J_2} + \alpha I_1 - K = 0 \tag{1}$$

where I_1 is the first variable of stress tensor, $I_1 = \sigma_{ii} = \sigma_1 + \sigma_2 + \sigma_3 = \sigma_x + \sigma_y + \sigma_z$; J_2 is the second invariant deviatory tensor of stress. $J_2 = \frac{1}{6}\left[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2\right]$; α and K are related parameters of internal friction angle φ and its cohesive force c of geotechnical materials.

2.3 Rock Mass Calculation Parameters

In the establishment of the numerical model, the stratified rock mass is a transversely isotropic elastoplastic constitutive relation, in all directions parallel to a plane (transverse), they all have the same properties, but are different from those in the vertical plane direction (longitudinal). The calculation parameters of rock mass model are selected according to article (Lian et al. 2010), as shown in Table 1.

2.4 Establishing the Numerical Model of Support Structure

The support structure was designed by using the straight wall arch chamber widely used in underground engineering, and numerical calculation models were established for four supporting conditions (rigid lining support, rigid lining and yielding anchor bolt combined support, flexible lining support and flexible lining and yielding anchor bolt combined support) respectively.

Numerical calculation model of lining structure: Both rigid lining and flexible lining were simulated by shell element. The rigid lining surface unit mesh covered the entire section of the tunnel, while the flexible lining set 60 mm elastic surface structure unit at the bottom to connect the two sides of the lining to simulate the flexible lining, so that it can have the compression deformation amount of 60 mm. The schematic diagram of lining support is shown in Fig. 4, and the specific parameters are shown in Table 2.

The numerical calculation model of the yielding anchor bolt structure: At present, the numerical model of the interaction between the yielding anchor bolt and tunnel surrounding rock is mainly simulated by commercial software, and the performance of the anchor bolt cannot be reflected by the calculation. This paper used the numerical model of the yielding anchor bolt structure in literature (Lian et al. 2010) to calculate. The yielding anchor bolt was in contact with the surrounding rock body through the anchorage section, while the bolt body was not in direct contact. The anchor core was simulated by two nodes bar element and the bar body did not contact with surrounding rock. A layer of solid element was set around the bar to simulate the contact of the adhesive directly with the surrounding rock. The pallet was simulated by rigid structure element, with annotatable constraints on both sides, and the prestress was applied to the pallet with uniform load. The bolt body was connected with the pallet by elastic connection, so that it had the yielding function. The characteristic parameters of the yielding anchor bolt were set: the yielding point RB = 165 kN, ultimate yielding distance D_{max} = 20 mm, and the ultimate compression and tensile load of the anchor bolt were both 235 kN.

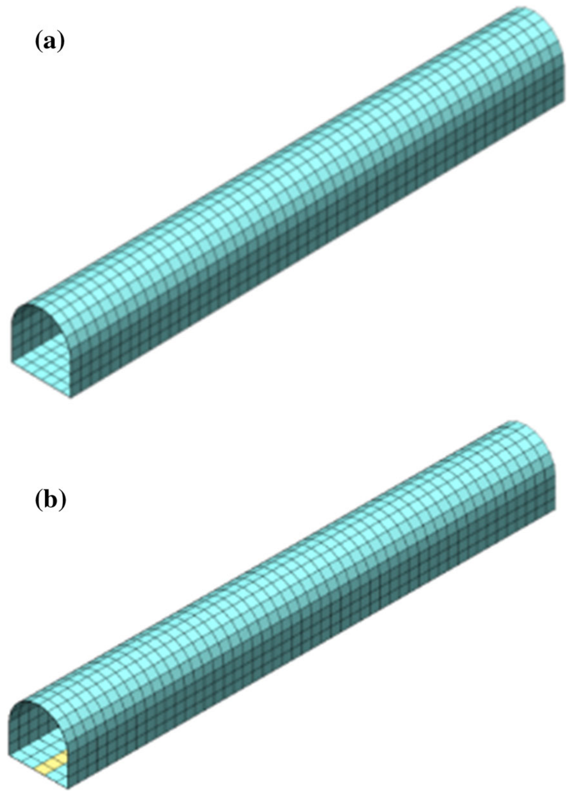


Fig. 4 The sketch map of lining support. **a** Rigid lining. **b** Flexible lining

Table 1 The Calculation parameters of rock mass model

Rock stratum category	γ (g/cm^3)	E (MPa)	σ (MPa)	φ (°)	c (MPa)	μ
Rock stratum 1	1.5	172	1.23	37.4	0.138	0.23
Rock stratum 2	1.4	126	0.92	32	0.092	0.27

Table 2 The Basic mechanical parameters of lining model

Material type	Thickness (mm)	Rigidity EI (MPa m^4)	Poisson ratio μ
Prototype lining	15	3.486	0.2

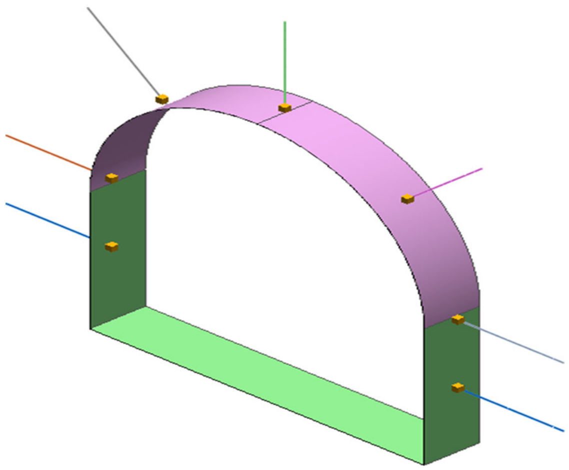


Fig. 5 The layout of model anchor bolt in the tunnel

The layout of the anchor bolt is shown in Fig. 5. The material parameters are shown in Table 3.

3 Analysis and Mechanism Research of Numerical Simulation Results

According to the calculation results of the numerical model of each supporting condition, the failure form of surrounding rock in deep tunnel, strain and displacement of surrounding rock of the tunnel and the internal force calculation results of the supporting structure were compared and analyzed, and the supporting effect and mechanical mechanism of the yielding structure of deep tunnel on the surrounding rock were studied.

Table 3 The material properties of yielding anchor bolt

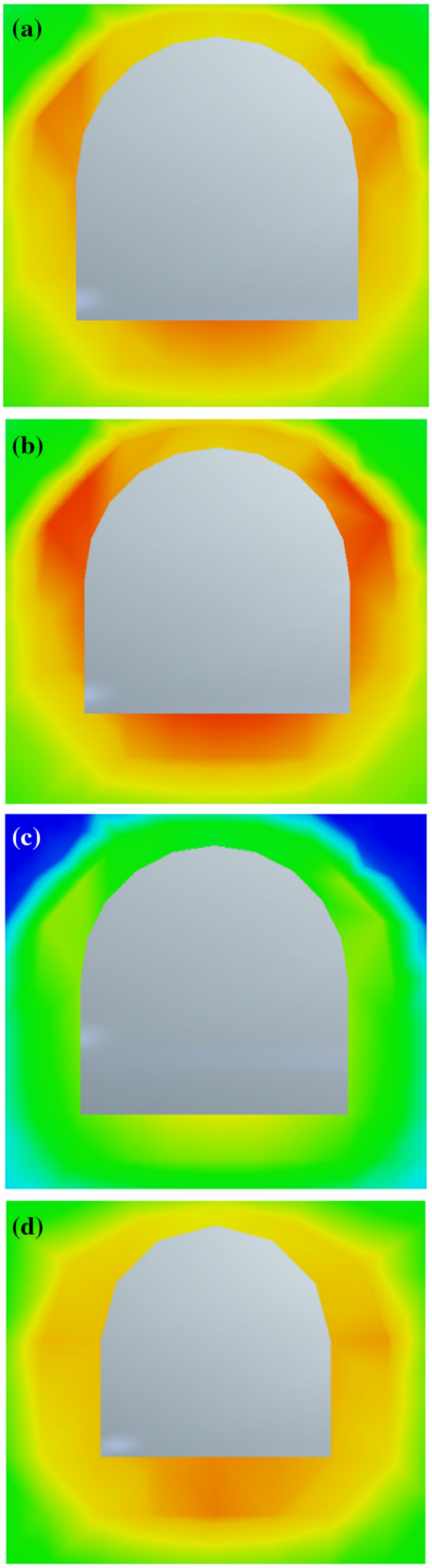
Material type	D (mm)	E (MPa)	μ
Anchor core	15.0	300	0.331
Adhesive	20.0	20	0.2

3.1 Analysis and Study on Failure Form of Tunnel Surrounding Rock

The four supporting conditions calculation models were calculated by using MIDAS numerical software to obtain the surrounding rock failure cloud map of each supporting condition. The surrounding rock failure cloud map of rigid lining tunnel is shown in Fig. 6a, the surrounding rock failure cloud map of flexible lining tunnel is shown in Fig. 6b, the surrounding rock failure cloud map of rigid lining and yielding anchor bolt tunnel is shown in Fig. 6c, and the surrounding rock failure cloud map of the flexible lining and yielding anchor bolt tunnel is shown in Fig. 6d.

By analyzing the tunnel surrounding rock failure cloud map of each supporting condition, it can show:

1. By analyzing the tunnel surrounding rock failure cloud map under four supporting conditions, it was found that the surrounding rock in each supporting condition had the characteristics of non-traditional failure and the failure area was close to the circle, indicating that the surrounding rock of tunnel still existed the zonal disintegration phenomenon under each support form. The supporting effects of the four supporting structures were: rigid lining and yielding anchor bolt > flexible lining and yielding anchor bolt > rigid lining > flexible lining.
2. By comparing the tunnel surrounding rock failure cloud map of rigid lining and flexible lining supporting structure, it was found that the failure of the surrounding rock on both sides of the flexible lining was more serious, while the failure of the rigid lining was more uniform. It was considered that because of the certain shrinkage capacity of the two sides of flexible lining, they cannot provide sufficient supporting force to the initial deformation of the surrounding rock, which lead to serious damage to the surrounding rock, and the failure of the surrounding rock was more



◀**Fig. 6** Tunnel surrounding rock failure cloud image of different supporting conditions. **a** The condition of Rigid lining support. **b** The condition of Flexible lining support. **c** The condition of Rigid lining and yielding anchor bolt support. **d** The condition of flexible lining and yielding anchor bolt support

uniform because of the better continuity of rigid lining.

3. Through the analysis of tunnel surrounding rock failure under the support of yielding structure, it was found that compared with the single lining supporting structure, the combined support structure of lining and yielding anchor bolt reduced the surrounding rock failure obviously, and inhibited the zonal disintegration of surrounding rock. It was considered that the anchor bolt played an anchorage effect on the tunnel surrounding rock after adding yielding anchor bolt, which connected the tunnel surrounding rock and the distant stable surrounding rock, realized the transfer of stress and reduced the destruction of the surrounding rock. At the same time, according to the article(Lian et al. 2008a, b), it can be found that the yielding performance of the yielding anchor bolt was equivalent to increasing the supporting strength of the supporting structure, improving the supporting role of the surrounding rock and reducing the fracture of the surrounding rock.

3.2 Analysis and Study on Strain and Displacement of Surrounding Rock

In order to facilitate the comparison and analysis of the results of the numerical calculation of the tunnel surrounding rock and the results of the physical model test, the displacement and strain values of the corresponding measured points in the fracture area and intact area were obtained in the position of the right wall with obvious damage in the numerical model chamber. The comparison results of the displacement and strain values of numerical model tunnel surrounding rock and physical model tunnel surrounding rock can be seen in Table 4, and the illustrative diagrams of the strain and displacement of the numerical model tunnel surrounding rock are drawn according to Table 4, as shown in Figs. 7 and 8.

Table 4 Numerical simulation and physical test results of different supporting conditions

Supporting conditions	Test method	The results	The number of measure point				
			1	2	3	4	5
Rigid lining support (the condition 1)	Numerical method	Displacement (mm)	1.056	0.546	0.971	0.612	0.245
	Test results		1.236	0.996	1.223	1.021	0.544
	Numerical method	Strain (10^{-6})	5.696	2.789	4.995	2.95	1.88
	Test results		5.781	3.133	4.598	3.112	2.223
Flexible lining support (the condition 2)	Numerical method	Displacement (mm)	1.756	0.846	1.665	0.564	1.032
	Test results		1.876	0.753	1.752	0.872	1.132
	Numerical method	Strain (10^{-6})	7.863	3.695	6.875	2.341	3.741
	Test results		6.667	2.897	5.873	1.865	2.031
Rigid lining and yielding anchor bolt support (the condition 3)	Numerical method	Displacement (mm)	0.542	0.237	0.445	0.388	0.376
	Test results		0.674	0.368	0.632	0.354	0.332
	Numerical method	Strain (10^{-6})	3.124	1.985	2.896	2.475	2.364
	Test results		3.741	2.224	3.542	2.248	2.074
Flexible lining and yielding anchor bolt support (the condition 4)	Numerical method	Displacement (mm)	0.774	0.345	0.781	0.478	0.416
	Test results		0.904	0.37	0.887	0.554	0.514
	Numerical method	Strain (10^{-6})	4.788	2.652	4.57	3.147	2.895
	Test results		5.032	2.75	4.865	3.245	2.897

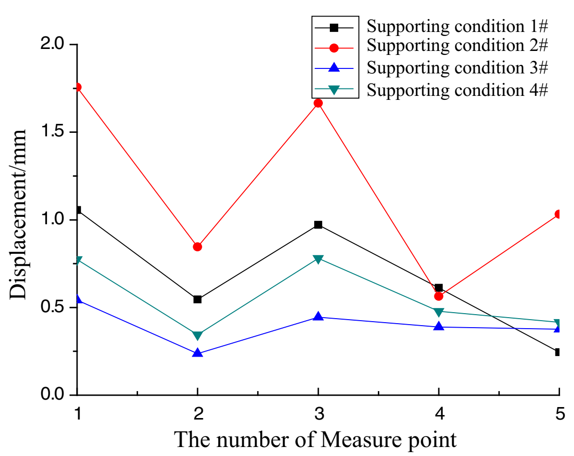


Fig. 7 Displacement curve of numerical model of various supporting conditions

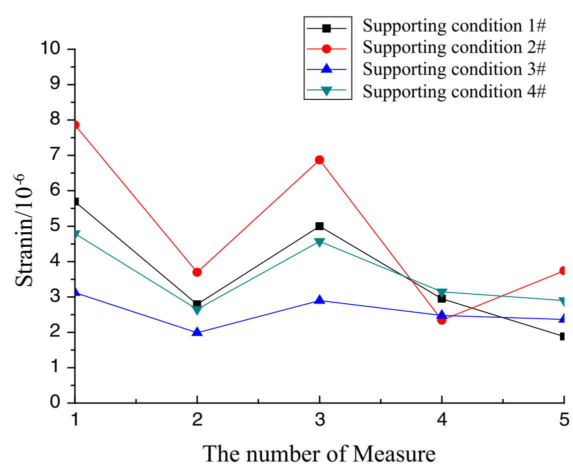


Fig. 8 Strain curves of numerical model of various supporting conditions

By analysing the results of strain and displacement of tunnel surrounding rock of various supporting conditions, it can be known that:

1. Through the comparison of the displacement and strain results of the tunnel surrounding rock of numerical model and physical model, it can be found that the tunnel surrounding rock under different supporting conditions all presented the wave change of strain and displacement curve, but not the traditional failure law that decreased with the increase of distance from the tunnel wall, indicating that the zonal disintegration phenomenon and trend still existed in the tunnel under the support result, which was basically consistent with the test results.
2. By comparing the displacement and strain results of the tunnel surrounding rock under different supporting conditions, under the support of rigid lining and yielding anchor bolt combined support structure, the zonal disintegration trend with the wave change of tunnel surrounding rock displacement and strain was obviously weakened, indicating that the yielding structure can suppress the zonal disintegration and weaken the zonal disintegration trend of the surrounding rock. The analysis showed that the yielding anchor bolt was added to make the tunnel surrounding rock form an anchorage body, which was associated with the remote stable rock mass to realize the transfer of stress and make the stress field distribution of surrounding rock uniform, so the strain and displacement of tunnel surrounding rock were relatively reduced, which inhibited the trend of zonal disintegration of surrounding rock. At the same time, the yielding performance of the yielding anchor bolt was equivalent to increasing the support strength of the supporting structure, reducing the tunnel surrounding rock failure, and maintaining the stability of the surrounding rock.

3.3 Analysis and Research on Internal Force of Lining Structure

In order to study the role of lining supporting structure in the deformation of surrounding rock and the supporting role of yielding anchor bolt on lining, the lining bending moment and strain numerical calculation results of vault, spandrel and side wall position under various supporting conditions were compared and analysed. The bending moment and strain value of the lining are shown in Table 5.

By analysing the internal force of lining support structure under various supporting conditions, it can be seen that:

1. Through the analysis of the internal forces of the vault, spandrel and side wall position of the lining support structure of various supporting conditions, the bending moment and strain value of the vault and side wall of the supporting structure were the greatest, indicating that the deformation of the vault and side wall of tunnel supporting structure was the largest, which was in good agreement with the observation results of actual supporting conditions.
2. By comparing the internal forces of the vault, spandrel and the side wall of the lining support structure in each supporting condition, it was known that compared with the single lining supporting structure, the bending moment and strain numerical calculation values of lining supporting and yielding anchor bolt combined supporting structure were obviously reduced. The analysis showed that after adding yielding anchor bolt, the tunnel surrounding rock formed more stable anchorage body which realized the transfer and redistribution of stress, made the distribution of stress field of tunnel surrounding rock more uniform, weakened the zonal disintegration trend of surrounding rock and achieved better support effect.

3.4 Analysis and Research on the Calculation Results of Internal Force of Yielding Anchor Bolt

The model tunnel was evenly divided into 10 excavation steps as shown in Figs. 9 and 10. The numerical calculation results of the internal force of anchor bolt on the lining of the right side of the tunnel with obvious damage in the numerical model were selected for analysis and research. The specific position diagram of the anchor bolt is shown in Fig. 10. The comparison results of the strain values between yielding anchor bolt numerical model and physical yielding anchor bolt model were shown in Table 6. According to Table 6, the illustrative diagram of strain

Table 5 Numerical calculation results of lining for each supporting condition

Supporting conditions	Numerical results	Lining position		
		Vault	Spandrel	Side wall
Rigid lining support	Bending moment (kN m)	4.23×10^2	1.48×10^2	3.32×10^2
	Strain (10^{-6})	1.21	0.42	0.95
Flexible lining support	Bending moment (kN m)	4.32×10^2	2.14×10^2	5.81×10^2
	Strain (10^{-6})	1.24	0.61	1.67
Rigid lining and yielding anchor bolt support	Bending moment (kN m)	3.15×10^2	1.06×10^2	3.05×10^2
	Strain (10^{-6})	0.90	0.31	0.87
Flexible lining and yielding anchor bolt support	Bending moment (kN m)	3.23×10^2	1.89×10^2	5.15×10^2
	Strain (10^{-6})	0.92	0.54	1.48

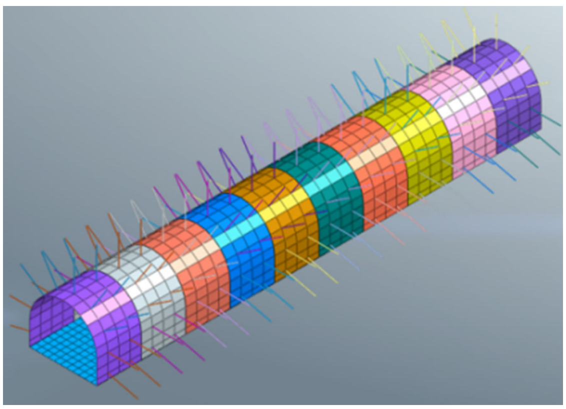


Fig. 9 Excavation step segmentation diagram of tunnel model

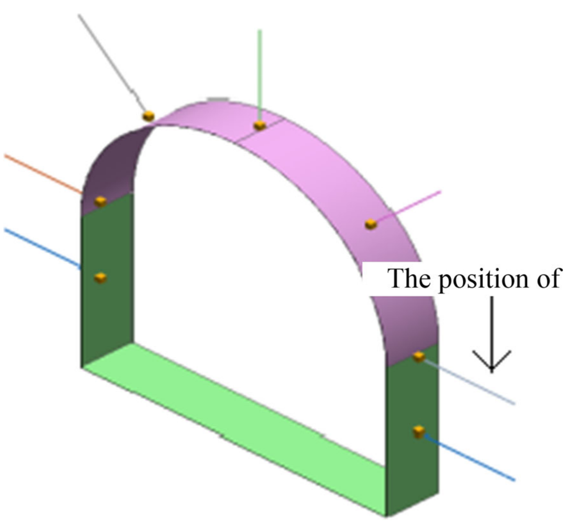


Fig. 10 Schematic diagram of anchor bolt position

change of numerical yielding anchor bolt was drawn as shown in Fig. 11. The numerical results of axial force and axial deformation of anchor bolt are shown in Table 7. The illustrative diagram of axial force and axial deformation was drawn according to Table 7, as shown in Fig. 12.

By analysing the calculation results of internal force of the anchor bolt, it can be known that:

1. Through the strain change of yielding anchor bolt in side wall position of the rigid lining combined support structure, we can find that in the early stage of the excavation, the strain value of the anchor bolt was negative, which indicated that the anchor bolt was pressed. When reaching the sixth step, the strain value of the anchor bolt turned to positive value, which showed that the anchor bolt was pulled, showing alternately changing law of "compression–tension" strain, which basically coincided with the strain law of the alternate tension and compression strain of the zonal disintegration of surrounding rock. According to the analysis of the strain change law, it can be seen that at the early stage of excavation, the anchorage body was pressed and deformed but had not been broken. At this time, the anchor blot was pressed, so the stain value was negative. With the excavation, the anchorage body began to break up, however, due to the anchoring effect of anchor bolt on surrounding rock of supporting area, the broken surrounding rock formed a new anchorage body, and at this time, the anchor bolt was pulled, so the strain value was positive. The strain law

Table 6 Strain numerical simulation and physical test results of yielding anchor bolt under different excavation steps

Supporting conditions	Test method	Test results	Excavation step									
			1	2	3	4	5	6	7	8	9	10
Rigid lining support	Numerical results	Strain (10^{-6})	3.67	4.12	2.12	5.77	6.13	1.12	2.05	4.23	4.31	4.56
	Test results		3.05	3.67	1.96	5.12	5.67	1.23	2.37	3.95	4.21	4.37
Flexible lining support	Numerical results	Strain (10^{-6})	1.05	1.75	1.81	2.12	2.23	3.15	4.21	5.21	5.32	5.75
	Test results		0.75	1.55	2.03	2.15	2.44	3.05	3.87	4.95	5.10	5.55

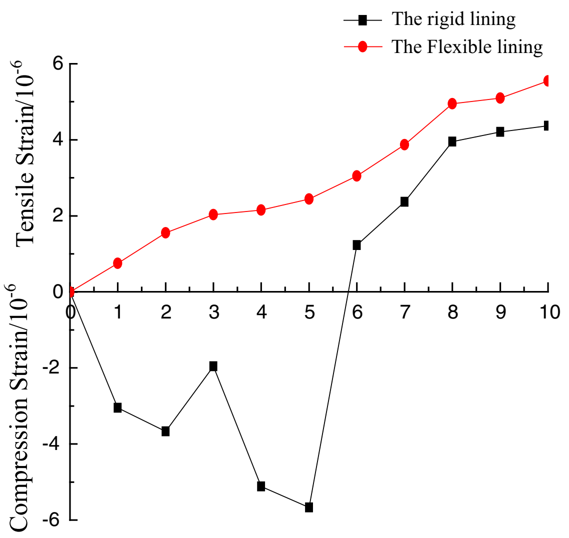


Fig. 11 Strain curves of yielding anchor bolt numerical model

showed that there was still a zonal disintegration trend in tunnel surrounding rock.

2. By analysing the phenomenon of strain change in the whole process of the excavation of the anchor bolt in the side wall location of the flexible lining combined support structure, it can be known that the strain value of the anchor bolt had always been positive, indicating that the anchor bolt had been pulled all the time, and there is no alternate change law of tension and compression strain. According to the analysis of this strain law, flexible structural spandrel and side wall location cannot provide enough supporting force at the early stage of excavation because of the compression deformation capacity, leading to rupture and deformation of tunnel surrounding rock. However, due to the anchoring effect of anchor bolts, the broken rock mass formed a new anchorage body. Therefore, during the whole excavation process, the anchor bolt was always pulled and the strain value was positive, indicating that the deformation of the surrounding rock in side wall and the spandrel of the flexible supporting structure was larger, and the surrounding rock was unstable.
3. Through the analysis of the axial force and the axial deformation of the anchor bolt, it was found that the deformation of the anchor bolt increased with the increase of the axial force before the axial force reached the yielding point load. When reaching the yielding load, the anchor bolt was continuously deformed with constant axial force, and the anchor bolt gradually entered the elastic yield stage when the deformation amount exceeded the ultimate yielding distance of anchor bolt. At the same, referring to literature (Lian et al.

Table 7 Numerical calculation results of axial force and axial deformation of anchor bolt under different excavation steps

Supporting conditions	Test results	Excavation steps									
		1	2	3	4	5	6	7	8	9	10
Rigid lining support	Axial force/kN	92.4	144.6	− 56.1	− 165	173.4	80.9	165	165	165	165
	Axial deformation/mm	− 5.6	− 8.7	− 3.4	− 10.7	− 20.8	4.9	11.6	14.1	14.5	14.9
Flexible lining support	Axial force/kN	59.4	95.7	122.1	161.7	165	165	165	165	200.5	217.7
	Axial deformation/mm	3.6	5.8	7.4	9.8	10.5	13.1	15.2	19.4	28.6	33.6

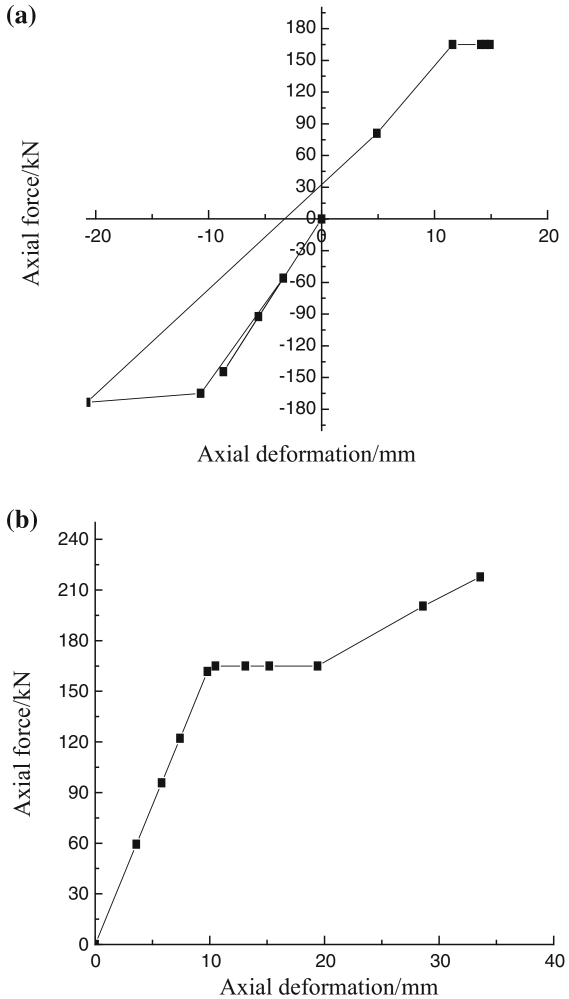


Fig. 12 Axial force and axial deformation diagram of yielding anchor bolt. **a** Rigid lining and yielding anchor bolt support. **b** Flexible lining and yielding anchor bolt support

2008a, b), we can see that the normal anchor bolt continued to deform under the axial force and rapidly entered the elastic yielding stage, resulting in the failure of damage. Under the same deformation, the axial force of the yielding anchor bolt was lower than that of the normal anchor bolt, which can prevent the failure of bolt because of premature yield, which had a protective effect on the bolt. The application of the yielding anchor can allow the surrounding rock anchorage to produce more stable deformation, which can effectively suppress the surrounding rock failure.

4 Conclusions

Through the analysis and study of the numerical calculation results we can find that the new combined support structure of rigid lining and yielding anchor bolt can effectively suppress the zonal disintegration of the surrounding rock of the deep tunnel. Therefore, the main conclusions of this paper are as follows:

1. By comparing the numerical model failure cloud map and the surrounding rock displacement and strain results of various supporting conditions, it can be found that the support effect of each supporting structure is in turn as follows: Rigid lining and yielding anchor bolt > flexible lining and yielding anchor bolt > rigid lining > flexible lining.
2. Through the numerical model failure cloud map and the surrounding rock displacement and strain results of various supporting conditions, it is found that under the support of each supporting structure, the surrounding rock still has the phenomenon of zonal disintegration. At the same time, the tunnel surrounding rock displacement and strain curves show a non-traditional destructive law of wave change, indicating that there is a trend of zonal disintegration in the surrounding rock.
3. Through the numerical calculation results of the internal force of the supporting structure, it is found that the combined support structure can make the tunnel surrounding rock form an effective anchorage body realize the transfer and redistribution of stress, and promote the stability of the surrounding rock. At the same time, the yielding anchor bolt can prevent the failure of bolt because of the premature yield, allow the anchorage body to produce more stable deformation, prevent the disintegration of the tunnel surrounding rock and effectively restrain the zonal disintegration of surrounding rock.
4. By analysing the mechanical mechanism of the yielding structure, the anchorage mechanism of the yielding structure is that the anchor bolt forms an effective anchorage body in the support area, which is connected with the remote stable surrounding rock, which enlarges the bearing ring of surrounding rock, realizes the transfer of stress, and changes the stress state of surrounding rock,

and inhibits the trend of zonal disintegration. Meanwhile, according to the combined arch theory the yielding distance can improve the support strength of the supporting structure and maintain the stability of the tunnel surrounding rock.

In conclusion, the new yielding combined support structure of rigid lining and yielding anchor bolt can effectively restrain the zonal disintegration phenomenon of deep tunnel surrounding rock and weaken the trend of zonal disintegration. Therefore, the layout of the yielding supporting structure has played a good supporting effect to the stability of the surrounding rock of the deep tunnel.

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