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OPTIMIZATION OF MECHANIZED RAPID CONSTRUCTION STEP DISTANCE FOR HARD ROCK BODY OF MA BAISHAN TUNNEL

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Abstract: This study aims to determine the rational construction safety step distance for hard rock tunnels, with the goal of effectively organizing the implementation of various construction processes to meet the requirements of rapid construction in hard rock tunnels. The FLAC3D finite difference software was utilized to establish a three-dimensional model based on the tunnel's cross-sectional form, excavation method, and support parameters, followed by numerical simulation analysis. The deformation patterns of the tunnel surrounding rock and the stress characteristics of the support structure under different construction step distances for II and III grade surrounding rocks were analyzed, and the stability of the tunnel surrounding rock and support structure was investigated. The results indicate that: 1) Under different rock grade conditions, as the tunnel construction step distance increases, the deformation of the tunnel surrounding rock and the stress on the initial support structure both show varying degrees of increase; 2) Considering the actual operation tool configuration and operational space requirements at the construction site of the Ma Bai Shan Tunnel, the bottom plate step distance for II and III grade surrounding rocks is adjusted to 300m, and the secondary lining step distance is adjusted to 400m, achieving the goal of rapid construction in hard rock tunnels while ensuring safety.

Keywords: Tunnel engineering; Mechanized construction; Hard rock formation; Step distance optimization

1 INTRODUCTION

With the rapid development of the global economy, more and more long tunnels have begun to emerge. However, as the scale of tunnel construction continues to expand, tunnel collapse accidents are becoming increasingly common [1-3], leading to severe casualties and property damage. Scholars, both domestically and internationally, have conducted investigative analyses of the causes and mechanisms underlying tunnel collapse accidents [4-5]. Research has revealed that the excavation of the invert arch has a significant impact on the deformation of the surrounding rock in tunnels [6]. Thus, it can be inferred that the inadequate safety distances during tunnel construction are a significant factor in causing tunnel collapse accidents. However, existing technical standards lack specific guidelines on the safe step distances for tunnel construction. Although Chinese railway construction documents [2008] No. 160 and [2010] No. 120 specify the invert arch and secondary lining step distances for tunnel projects, the prescribed values are determined based on engineering experience, relying solely on a simple classification according to rock mass levels and fail to comprehensively consider factors such as groundwater conditions, support conditions, and construction plans [7]. To ensure construction safety, construction units often opt for smaller safety step distances. However, with the increasing mechanization of tunnel construction, more and more large machinery is being used to replace manual labor throughout the entire tunnel construction process to ensure the rapid construction of tunnels [8-9]. Consequently, the excessively conservative step distance requirements pose significant obstacles to the placement of large machinery on-site, severely impacting the progress of current tunnel construction. In response to such issues, numerous scholars at home and abroad have updated the invert arch and secondary lining step distances for tunnels based on typical engineering cases, employing various approaches.

Tong Kai [10], based on the V-grade surrounding rock section of the Zhengwan High-speed Railway Xinhua Tunnel, conducted corresponding research on the secondary lining and face safety step distances under different burial depths in the construction tunnel, using the elastic foundation beam theory. Using both mechanical models and numerical simulations, the maximum construction step distance was determined to be 60 meters. Hao Junming [11], relying on the Heping Tunnel and Chongli Tunnel projects in the Tai-Chong section of the Tai-Xi Railway, established village lining and invert arch models under different construction step distances using FLAC numerical simulation software. The study explored the step distances for the inclined arch and secondary lining construction under different rock mass construction levels when meeting the requirements of mechanized rapid construction. Wang Haizhou [12] derived a formula for calculating the safe step spacing, taking into account seven influencing parameters. This formula was successfully applied to an actual project. Shi Jiyao et al. [13] relied on the Guchengling Tunnel of BaoLan Hub to establish a numerical model that accurately reflects the actual engineering practice. Their study aimed to analyze the deformation characteristics of large section tunnels with soft rock and investigate the impact of the elevated arch step distance and step length on the deformation of the initial support; Zhou Xueliang [14] collected a large amount of data on the collapse of the Dongshan tunnel. He combined this data with monitoring data on the deformation trend of the surrounding rock to conduct a comprehensive prediction. He studied the relationship between the deformation of the section, the excavation time, and the spacing of the palm face of the second lining. This study aimed to determine the optimal timing for applying the second lining; R.B. ROKAHR [15] selected five tunnels with similar mechanical parameters of the surrounding rock for analysis and comparison, selected the appropriate support parameters, and calculated the construction step under different surrounding rock conditions in the case, and finally determined the optimum safety step value for this tunnel.

In summary, for the relatively understudied optimization of step distances in Grade II and III hard rock tunnels, this study relies on the Grade II and III hard rock sections of the Ma Bai Shan Tunnel in the Qinling Mountains to conduct research on step distance optimization. The objective is to propose a long-distance safety step distance that meets the requirements of full-face excavation using large machine excavation and the corresponding support conditions, thereby achieving rapid construction in hard rock tunnels.

2 PROJECT OVERVIEW

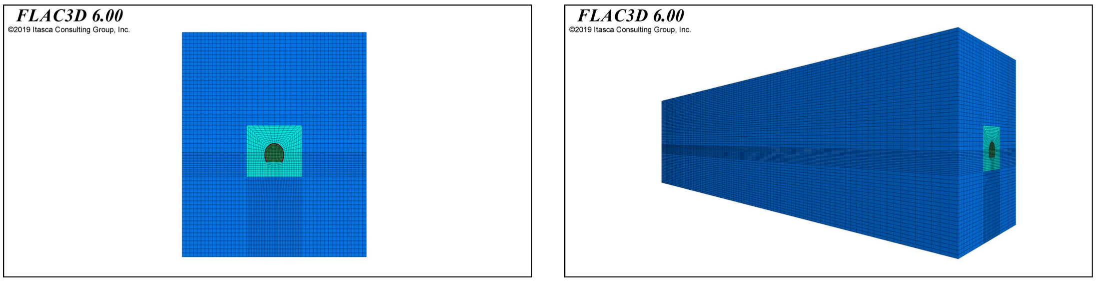
The Qinling Ma Bai Shan Tunnel is located in the jurisdictions of Lantian County, Shaanxi Province, and Shangluo City. It is a dual-bore, single-track tunnel with a total length of 22,918 meters. Grade II and Grade III surrounding rocks account for 75.5% of the total length of the tunnel. It is a high-speed railway tunnel traversing large segments of hard rock formations. In the project area, the overall distribution of the Qinling mountain range trends northeast, with elevations ranging from 800 to 2000 meters and a relative height difference of 500 to 1000 meters. The northern slope of the Qinling Mountains is steep, characterized by short gullies, steep longitudinal slopes in the gully beds, and a general pattern of "U"-shaped valleys in the upper reaches and "V"-shaped valleys in the lower reaches with steep slopes. The southern slope has longer gullies and often exhibits a tree-branch-like water system.

The left line of the tunnel extends from DK46+393 to DYIIK69+311, with a total length of 22,918 meters and a maximum depth of burial of 620 meters. The tunnel's right line extends from DYIIK46+393 to DYIIK69+312, covering a total length of 22,919 meters and reaching a maximum burial depth of 620 meters. In the tunnel alignment area, with the exception of a small amount of Quaternary artificial fill and alluvial layers within the gullies, the bedrock is exposed in other sections. In exposed layers, the predominant geological formations consist of quartzite from the Middle-Lower Cambrian Kuanping Group's Sichakou Formation, sericite-chlorite-quartz schist from the Zhulin Formation, and granite from the Yanshan period. The tunnel passes through the fractured zone of the F8 fault and, in addition, traverses several areas with densely packed joint systems. The overall geological conditions of the tunnel are characterized by predominantly weak to moderately water-rich rock formations, with the presence of adverse geological conditions such as hazardous rockfall, significant deformation in soft rock, and high ground stress.

3 NUMERICAL SIMULATION AND SIMULATED WORKING CONDITIONS

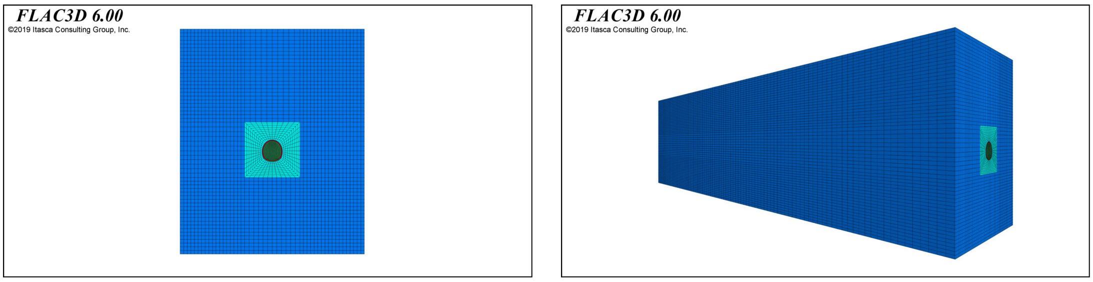
3.1 Computational Modeling

Combined with the current construction situation of the tunnel, the FLAC3D finite difference software is utilized to create a numerical simulation 3D model. According to previous experience with tunnel excavation simulation modeling, in order to minimize the impact of boundary effects, the model boundary is set at 3~5 times the diameter of the hole, considering the setup of the tunnel safety step, the model is taken as 450m in the longitudinal direction. Therefore, the dimensions of the 3D simulation model for the level II surrounding rock are selected as: 450m×100m×130m (length×width×height). Similarly, the dimensions of the 3D simulation model for the level III surrounding rock are also selected as: 450m×100m×130m (length×width×height). The displacement boundary adopts fixed boundary conditions, with horizontal constraints on the left and right sides of the tunnel, vertical constraints on the lower part, constraints perpendicular to its surface on the front and back, and a free boundary on the ground surface. The overall Moore Cullen model is used before excavation, and the initial support and secondary lining during excavation are simulated using elastomeric units after rigidity equivalence. The initial support and secondary lining are both calculated using solid units for consistent calculation. The three-dimensional simulation model of Class II rock tunnel is shown in Figure 1. The three-dimensional simulation model of Class III rock tunnel is shown in Figure 2.



(a) Front View (b) Oblique View

Figure 1 Three-Dimensional Simulation Model of Class II Perimeter Rock Tunnel



(a) Front View (b) Oblique View

Figure 2 Three-Dimensional Simulation Model of Class III Perimeter Rock Tunnel

3.2 Parameter Selection

The physical and mechanical parameters of the tunnel surrounding rock and lining structure are selected according to the "Design Code for Railway Tunnels" (TB 10003-2016) and "Design Code for Concrete Structures" (GB50010-2010). The simulated physical and mechanical parameters of the tunnel excavation with Class II surrounding rock are shown in Table 1, while those of Tunnel Excavation with Class III Surrounding Rock are shown in Table2. The physical and mechanical parameters of the initial support concrete are shown in Table 3.

Table 1 Physical and Mechanical Parameters of Class II Surrounding Rock Model

materials	Modulus of deformation E(GPa)	Heaviness γ (KN/m^3)	Poisson's ratio (μ)	Angle of internal friction θ (°)	Adhesion cohesion c (MPa)	thicknesses (m)
surrounding rock	27	27	0.25	54	1.8	
Initial support	23	23	0.2			0.05
secondary lining	31.5	25	0.2			0.3

Table 2 Physical and Mechanical Parameters of Class III Surrounding Rock Model

materials	Modulus of deformation E (GPa)	Heaviness γ (KN/m^3)	Poisson's ratio (μ)	Angle of internal friction θ (°)	Adhesion cohesion c (MPa)	thicknesses (m)
surrounding rock	14	25	0.3	44	1.0	
Initial support	23	23	0.2			0.10
secondary lining	31.5	25	0.2			Arch wall 0.35/Elevation arch 0.40

Table 3 Physical and Mechanical Parameters of Initial Concrete

Concrete grade	Heaviness γ (KN/m^3)	Modulus of deformation E(GPa)	Poisson's ratio (μ)	compressive strength (MPa)	tensile strength (MPa)
C25	23	23	0.2	19.0	2.0

4 OPTIMIZATION OF MECHANIZED RAPID CONSTRUCTION STEPS

Currently, the construction step distance requirements for the Ma Bai Shan Tunnel site are as follows: for Grade II surrounding rock sections, the distance from the base plate to the face is 200m, and the distance for the secondary lining is 300m; for Grade III surrounding rock sections, the distance from the invert to the face is 90m, and the distance for the secondary lining is 120m. However, due to the utilization of large-scale mechanized equipment on-site, the space required for a complete mechanical construction operation line is relatively large. The original step distance conditions cannot meet the construction requirements. It is necessary to moderately expand the current construction step distance based on the actual situation of on-site monitoring and measurement and the space requirements of large-scale mechanized equipment. The specific step distance optimization schemes for different rock grades in this numerical simulation are detailed in Table 4 and Table 5:

Table 4 Setting of Safety Step Distances for Grade II Surrounding Rock

working condition	Base plate distance/m	Second liner distance /m
Actual walking distance in Mabai Mountain	200	300
Step program I	250	350
Step program II	300	400

Table 5 Setting of Safety Step Distances for Grade III Surrounding Rock

working condition	Base plate distance /m	Second liner distance /m

Actual walking distance in Mabai Mountain	120	200
Step program I	200	300
Step program II	300	400

4.1 Analysis of Surrounding Rock Monitoring and Measurement Results

The stable final value curves of the arch crown settlement and horizontal convergence for five cross-sections in the Grade III surrounding rock section, obtained from on-site monitoring, are shown in Figure 3:

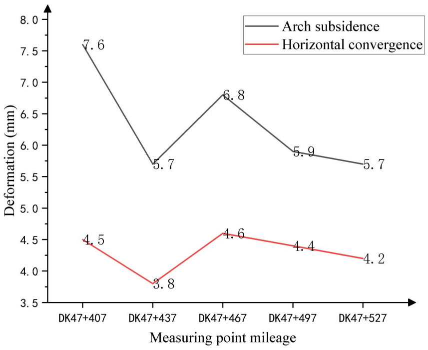


Figure 3 Final Value Curves of Arch Crown Settlement and Horizontal Convergence Deformation for Grade III Surrounding Rock

Combining the results shown in Figure 3, the cumulative settlement deformation of the arch crown for Grade III surrounding rock is not greater than 8mm, and the cumulative deformation of horizontal convergence is not greater than 5mm. The final values at monitoring points show minimal fluctuations, indicating stability. For Grade II surrounding rock, based on on-site monitoring data, its deformation pattern is consistent with Grade III surrounding rock, but with slightly smaller final values. The cumulative settlement of the arch crown deformation is not greater than 6mm, and the cumulative convergence of horizontal deformation is not greater than 3mm. The overall monitoring data of the surrounding rock indicates stability, and the deformation of the rock has not reached the deformation limits of Grade II and Grade III surrounding rocks. This provides favorable conditions for expanding the construction step distance.

4.2 Simulation Results of Step Optimization for Grade II Surrounding Rock

With regard to the influence of different base plate and second lining step distance on the deformation of Class II surrounding rock and the force on the supporting structure, the analyses of the deformation of the tunnel and the force on the initial support in combination with the simulation results are concluded as follows:

4.2.1 Surrounding rock displacement analysis

For different step distances in Grade II surrounding rock, the arch crown settlement and horizontal convergence curves for monitoring cross-sections are shown in Figure 4 and Figure 5:

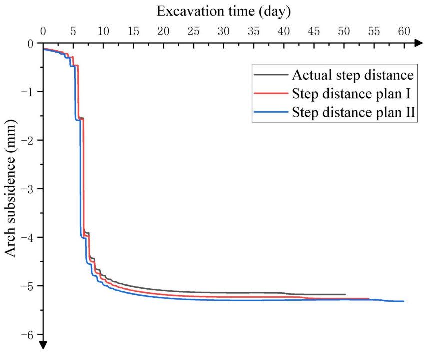


Figure 4 Comparison Curve of Arch Subsidence

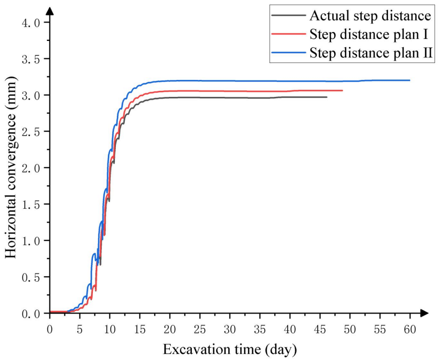


Figure 5 Comparison Curve of Horizontal Convergence

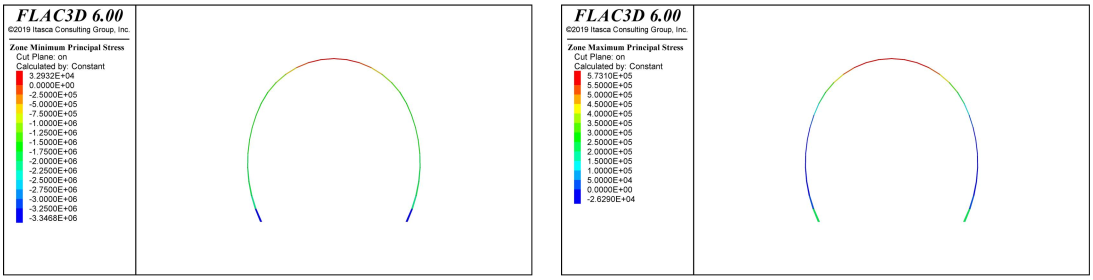
1) According to Figure 4, it is evident that under different safety step distances, the settlement of the tunnel arch shows a characteristic of initial settlement followed by stabilization. However, with the increase in the calculated safety step distance, the stable final value of tunnel arch settlement also increases. In the case of the Ma Baishan Tunnel under actual step distance conditions, the settlement of the arch is 5.18mm. From a safety perspective, this value meets the

requirements for on-site construction safety. For Step Distance Scheme 1, the arch settlement is 5.26mm, and for Step Distance Scheme 2, it is 5.32mm, which is the maximum value in this calculation. From the perspective of arch settlement, the simulation results under the three step distance conditions still fall within the deformation limit of a Class II surrounding rock tunnel, demonstrating that they all meet the safety construction requirements at the site.

2) According to Figure 5, it is observed that the horizontal convergence of the tunnel monitoring section exhibits a characteristic of initial increase followed by stabilization under different safety step distances. However, as the calculated safety step distance increases, the stable value of tunnel horizontal convergence also increases. In the case of the Ma Baishan Tunnel under actual step distance conditions, the horizontal convergence is 2.97 mm, meeting the requirements for safe on-site construction. For Step Distance Scheme 1, the horizontal convergence is 3.06mm, and for Step Distance Scheme 2, it is 3.20mm, with the maximum horizontal convergence occurring under Step Distance Scheme 2. From the perspective of horizontal convergence, the results under three schemes demonstrate that they meet the safety requirements for on-site construction of a Class II surrounding rock tunnel.

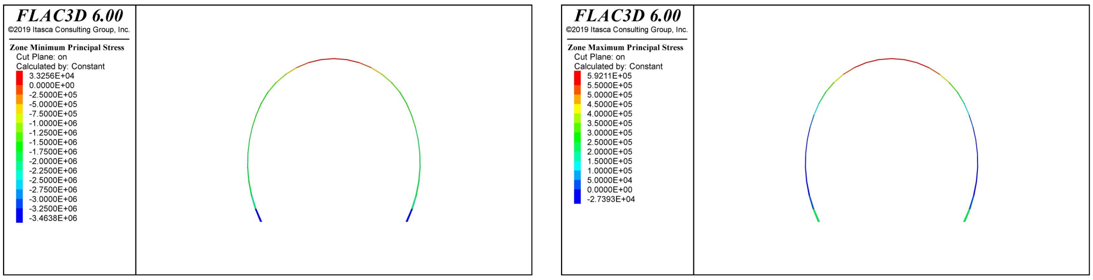
4.2.2 Initial support stress analysis

The initial support stress of the tunnel under different conditions for Class II surrounding rock are shown in Figure 6 to 8:



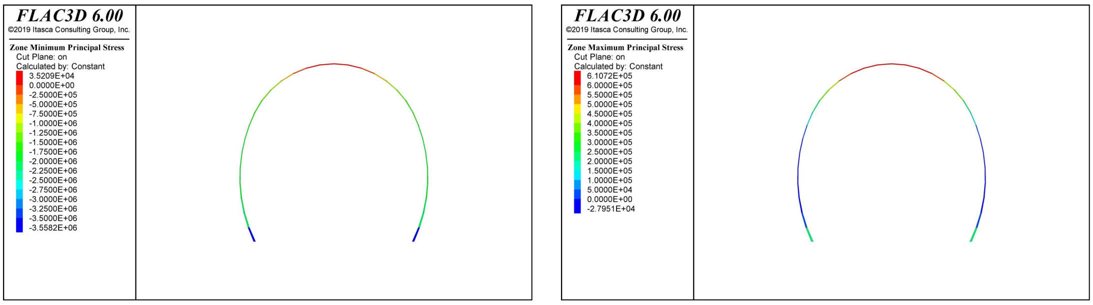
(a) Maximum Principal Stress Map (b) Minimum Principal Stress Map

Figure 6 Initial Support Stress Diagram for Actual Step Distance Conditions



(a) Maximum Principal Stress Map (b) Minimum Principal Stress Map

Figure 7 Initial Stress Diagram for Step Distance Scheme I



(a) Maximum Principal Stress Map (b) Minimum Principal Stress Map

Figure 8 Initial Stress Diagram for Step Distance Scheme II

According to Figure 6 to 8, it is observed that as the safety step distance increases, there is a slight increase in both the maximum and minimum principal stresses in the initial support structure of the tunnel. Under actual step distance conditions in the Ma Baishan Tunnel, the maximum compressive stress is 3.35 MPa, and the maximum tensile stress is 0.57 MPa, representing the minimum values in the simulation results and meeting the safety requirements for on-site construction. For Step Distance Scheme 1, the initial support's maximum compressive stress is 3.46 MPa, and the maximum tensile stress is 0.59 MPa. Under Step Distance Scheme 2, the initial support's maximum compressive stress is 3.56 MPa, and the maximum tensile stress is 0.61 MPa. In Step Distance Scheme 2, the initial support experiences the maximum load, but these values still fall within the ultimate stress range of C25 concrete, ensuring the safety of the initial support structure.

4.3 Simulation Results of Step Optimization for Grade III Surrounding Rock

In consideration of different construction step distance conditions for Class III surrounding rock, combined with the computational simulation results, an analysis of the deformation and initial support stress situations in Class III surrounding rock is provided, and the conclusions are as follows:

4.3.1 Analysis of surrounding rock displacement

Under different step distance conditions for Class III surrounding rock, the curves depicting the tunnel arch settlement and horizontal convergence for the monitoring section are presented in Figure 9 and Figure 10, respectively.

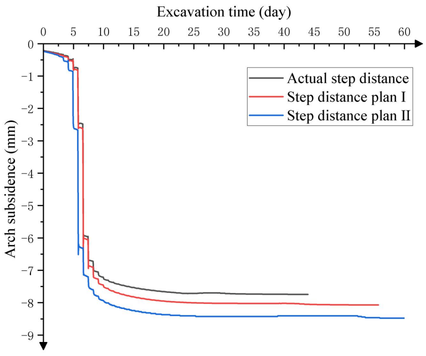


Figure 9 Comparison Curve of Arch Subsidence

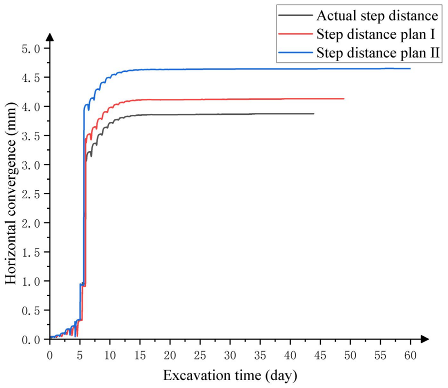


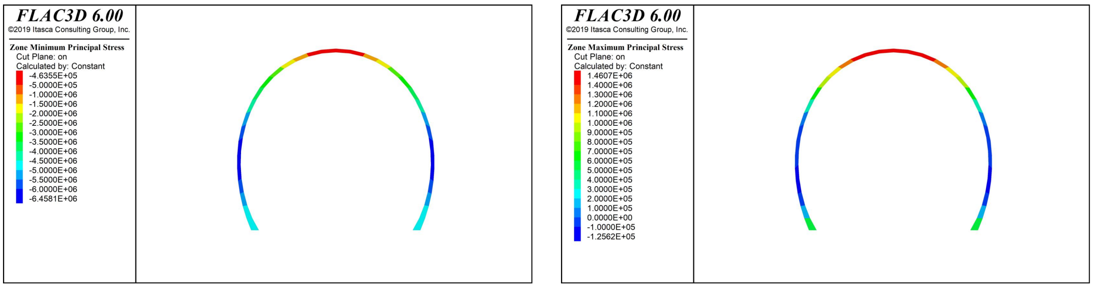
Figure 10 Comparison Curve of Horizontal Convergence

1) As can be seen from the Figure 9, it is evident that under different safety step distances, the tunnel's arch settlement exhibits characteristics similar to those observed in Class II surrounding rock conditions. Specifically, for the Ma Baishan Tunnel under actual step distance conditions, the arch settlement is 7.74mm. For Step Distance Scheme 1, the arch settlement is 8.06mm, and for Step Distance Scheme 2, it is 8.47mm, with the maximum arch settlement occurring under Step Distance Scheme 2. From the perspective of arch settlement, all three schemes are considered sufficient to meet the safety requirements for on-site construction.

2) As depicted in Figure 10, it is evident that under different safety step distances, the horizontal convergence of the tunnel monitoring section exhibits a characteristic of initial increase followed by stabilization, consistent with the convergence features observed in Class II surrounding rock. However, as the calculated safety step distance increases, the stable value of tunnel horizontal convergence also increases. Specifically, for the Ma Baishan Tunnel under on-site step distance conditions, the horizontal convergence is 3.87mm. For Step Distance Scheme 1, the horizontal convergence is 4.13mm, and for Step Distance Scheme 2, it is 4.65mm. From the perspective of horizontal convergence, all three schemes are deemed sufficient to meet the safety requirements for on-site construction.

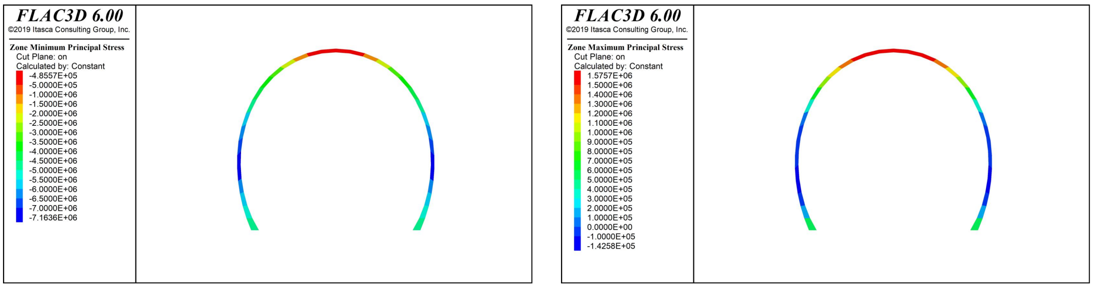
4.3.2 Initial support stress analysis

Tunnel initial stresses under different working conditions of Class III surrounding rock are shown in Figure 11 to 13:



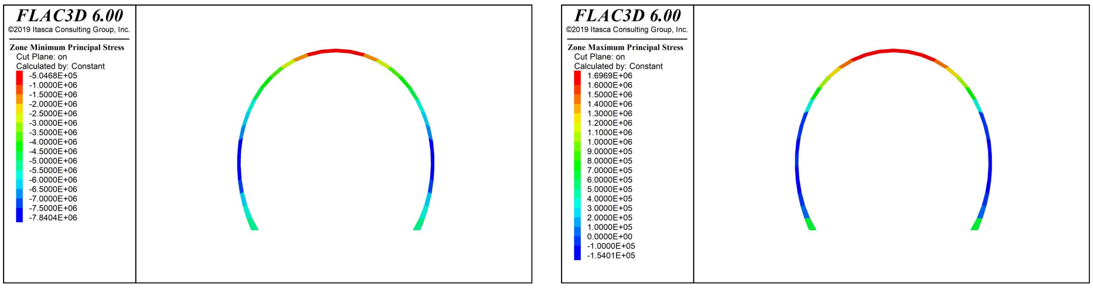
(a) Maximum Principal Stress Map (b) Minimum Principal Stress Map

Figure 11 Initial Support Stress Diagram for Actual Step Distance Conditions



(a) Maximum Principal Stress Map (b) Minimum Principal Stress Map

Figure 12 Initial Stress Diagram for Step Distance Scheme I



(a) Maximum Principal Stress Map (b) Minimum Principal Stress Map

Figure 13 Initial Stress Diagram for Step Distance Scheme II

According to Figure 11 to 13, it is evident that with the increase in safety step distance, both the maximum and minimum principal stresses in the tunnel's initial support structure experience a certain degree of increment. Specifically, for the Ma Baishan Tunnel under actual step distance conditions, the maximum compressive stress is 6.46 MPa, and the maximum tensile stress is 1.46 MPa. For Step Distance Scheme 1, the initial support's maximum compressive stress is 7.16 MPa, and the maximum tensile stress is 1.58 MPa. Under Step Distance Scheme 2, the initial support's maximum compressive stress is 7.83 MPa, and the maximum tensile stress is 1.69 MPa. In Step Distance Scheme 2, the initial support experiences the maximum load, but these values still fall within the ultimate stress range of C25 concrete, achieving the goal of safe construction.

4.4 Determination of Mechanized Construction Step Distances

As shown in Figure 14, to achieve mechanized and rapid construction of the single-lane tunnel in the hard rock body of Ma Baishan, large-scale mechanized equipment such as three-wall rock drilling trolleys are used to carry out mechanized excavation of the whole operation line, and the configuration of the main machinery and equipment is shown in Table 6:

Figure 14 Three-Arm Rock Drill Dolly

Table 6 Configuration Table for Mechanized Construction Equipment

serial number	operating line	Name of equipment/machinery	Brand/Model/Specification	quantities	note
1	scoop out	Fully computerized three-armed rock drill	ZYS113	1	Walking, rock drilling operations, charging operations
2		Full Section Excavation Bench	self-restraint	1	Excavation, support
3		wind-powered rock drill	YT28	20	Excavation drilling, Anchor drilling
4	shipment	Loaders (side discharge)	ZC50	2	mount a ballast
5	support	abutment	self-restraint	1	Initial support
6	spray concrete	Concrete wet sprayer	Tiejian Heavy Industry HPS3016SW /30m³/h	1	Supporting concrete spraying
7	a vault	a pierced trestlework	self-restraint	1	Arch construction
8	anti-drainage	Watertight Sheet Bench	self-restraint	2	Waterproof layer construction
9	second lining	Second lining cart	Zhuozhou Machinery Factory/12m	2	Lining Concrete Pouring

Considering the current machinery configuration, it is evident that the existing construction step distance conditions are insufficient to meet the requirements of the current mechanized construction across the entire line. Based on on-site monitoring data and numerical simulation results, it has been observed that for Class II and Class III surrounding rock, appropriately increasing the construction step distance does not significantly impact on the deformation of the surrounding rock and the stress on the tunnel support structure. This adjustment does not compromise the safety of on-site construction. Therefore, integrating the numerical simulation results with the practical requirements for the space needed in large-scale mechanized construction, the construction step distance for the base plate in Class II and Class III surrounding rock is ultimately adjusted to 300m, and the second lining step distance is adjusted to 400m.

5 CONCLUSION

This paper updates and optimizes the safety step distance for large-scale mechanized construction of the main tunnel of Ma Baishan Tunnel with Class II and Class III surrounding rocks. The main conclusions are as follows:

1) In terms of the deformation of the surrounding rock in the tunnel, it can be observed that, under the same rock classification, as the safety step distance increases, the settlement of the vault initially increases and then stabilizes. Similarly, the horizontal convergence initially increases and then remains stable. Both tunnel arch settlement and horizontal convergence show a slight increment with the enlargement of safety step distance.

2) In terms of the stresses on the support structure of the tunnel, the maximum compressive stresses on the Class II surrounding rock support structure are mainly distributed at the left and right footwalls of the tunnel due to stress concentration. The maximum compressive stresses on the Class III surrounding rock support structure are mainly located at the sidewalls. The maximum tensile stresses occur at the arch shoulders of the tunnel. With an increase in safety step distance, there is a slight increase in the maximum compressive and tensile stresses on the tunnel support structure.

3) The calculations show that the deformation of the tunnel surrounding rock and the force of the supporting structure will increase to a certain extent under the increased step spacing of Class II and III surrounding rock, but when the construction step spacing reaches the maximum, the deformation of the tunnel has not yet reached the limiting deformation value of the Class II and III surrounding rock, and the force of the supporting structure is also within the limiting stress range of C25 concrete. The support structure is still in a safe state. Therefore, the construction step distance for the base plate in Class II and Class III surrounding rock is adjusted to 300m, and the second lining step distance is adjusted to 400m, facilitating the subsequent implementation of large-scale mechanized construction.

COMPETING INTERESTS

The authors have no relevant financial or non-financial interests to disclose.

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