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Structural Safety Impact Analysis of New High Speed Rail Tunnel with Small Clearances under Highway Tunnel

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Abstract: In recent years, there are more and more road-railway crossings, among which road tunnels intersecting with railroad tunnels with small clearances is one of the crossings with higher safety risks. In order to analyze the impact of the new tunnel construction on the safety of the existing tunnel structure, the deformation of the existing tunnel at different stages of the new tunnel excavation was analyzed and calculated using the stratigraphic structure method modeling. The results show that the new tunnel under the existing tunnel excavation to the existing tunnel directly below the intersection of the location of the plastic zone through, the impact of this construction time should focus on strengthening the over-support protection; under the tunnel excavation caused the largest vertical displacement of the existing tunnel above, and the vertical displacement with the new tunnel excavation below the scale of increasing. The study shows that the main impact during the construction of new tunnels with small clearances through existing tunnels is the plastic zone penetration and vertical deformation of the cross section, which should be combined with construction excavation measures and overrun support design to take the necessary safety protection means.

1. Introduction

With the continuous development of China's transportation infrastructure construction, the road mileage and railroad mileage are increasing[1,2], and there are more and more road and railroad crossings in recent years, among which the intersection of road tunnel and railroad tunnel with small clearances is a type of crossings with high safety risk in public-rail crossings. Xu Ke and Lu Shasha[3,4] conducted a finite element simulation for the deformation of railroad roadbed in the construction of public-rail crossings, and proposed the main safety factors and the corresponding safety risk assessment system and assessment indexes in the construction of public-rail crossings; Heidarzadeh et al.[5] conducted a numerical simulation for underground tunnel excavation, mainly analyzed the stress path and deformation around the tunnel, and proposed a Jin D.L. et al.[6,7] studied the settlement and deformation characteristics of shield tunnels under existing tunnels; Zhengping Xian[8] used finite element numerical simulation to analyze the changes in the force and safety coefficients of railroad tunnel structures before and after the application of highway loads; Bin Huang[9] studied the structural safety of new tunnels under different construction methods of existing tunnels based on the finite element Moore-Cullen principle. Zhao Yucheng[10] analyzed the mutual influence of small clearance cross tunnels under different construction sequences by numerical simulation; some scholars[11,12] studied the structural stress and safety of second lining of large deformation tunnel and tunnel in mining area; Wen Xin[13] studied the stability of cross tunnels under four different construction methods by numerical simulation.

In order to ensure that the impact of new tunnels on the safety of existing tunnel structures is within acceptable limits, a corresponding safety technical evaluation needs to be carried out during the design phase. In this paper, a new high speed railway tunnel with small clearances underneath an existing highway tunnel was designed as an example, and the deformation of the existing tunnel at different stages of the new tunnel excavation was analyzed and calculated using the stratigraphic structure method modeling. The results show that the new tunnel under the existing tunnel excavation to the existing tunnel directly below the intersection of the location of the plastic zone penetration, the impact is large, the construction time should focus on strengthening the over-support protection; under the tunnel excavation caused the largest vertical displacement of the existing tunnel above, and vertical displacement with the new tunnel excavation below the footage increasing.

2. Project Overview

The new Xi'an-Chongqing high-speed railroad (hereinafter referred to as "West-Chongqing high-speed railroad") project is an important part of the national "eight vertical and eight horizontal" high-speed railroad channel of the package (silver) sea, Beijing-Kunshan channel, southwest and northwest, northeast China, Guangxi-Hainan and northwest railroad passenger transport The project is positioned as a high-speed railroad channel with inter-regional passenger flow as the main channel, and inter-city passenger flow along the route is taken into account.

West Chongqing high-speed railway Xujiapo tunnel tunnel is located in Chongqing Hechuan East ~ Beibei South interval, a single-hole double-line tunnel, design speed 350km/h, the total length of 4776m. Tunnel import connected to the Tianfu Jialing River Special Bridge bridge platform; export connected to the roadbed. This tunnel DK445+300~DK445+412 section under the Lanhai Expressway Beibei tunnel, the new high-speed railway tunnel buried 52 ~ 66m, the existing highway tunnel buried 33 ~ 35m; plane intersection angle of about 80°, plane intersection point, the new high-speed railway tunnel structure bottom and the existing highway tunnel structure top vertical distance of about 13.30m, the railroad tunnel and highway tunnel intersection section plane location relationship and the longitudinal section are shown in Figure 1 and Figure 2. This section is excavated by CRD method and mechanical excavation is used. The tunnel is lined with V/t lining, full-ring I22b steel frame and D159 overrun large pipe shed grouting in the arch to strengthen the support.

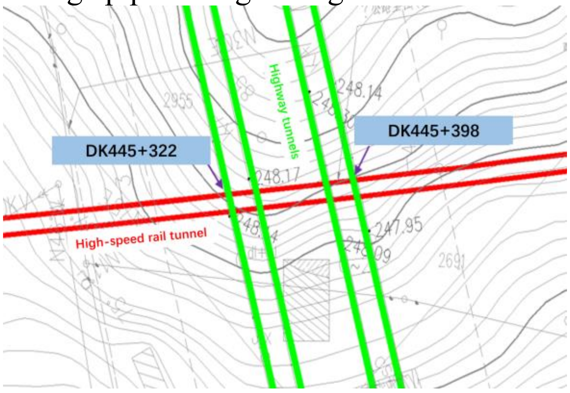


Figure 1: Plane position relationship

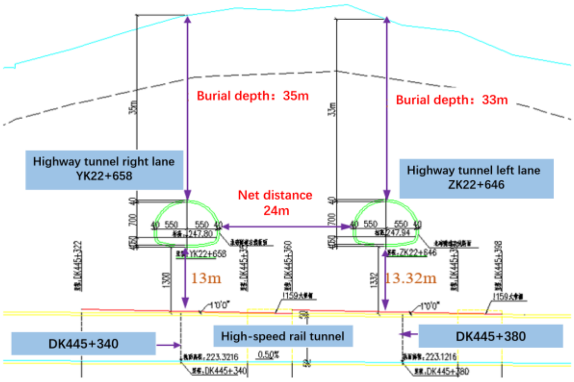


Figure 2: Longitudinal section position relationship

3. Calculation Scheme

3.1. Calculation Method Selection

The common calculation theories for tunnel structure analysis are stratigraphic structure method and load structure method. The stratigraphic structure method mainly includes the rationalization simulation of stratigraphy, structure simulation, construction process simulation and the simulation of the interaction between structure and surrounding strata and the interaction between strata and structure during the construction process. The calculation theory of stratigraphic structure model is the stratigraphic structure method, whose principle is to consider the lining and strata as a whole, calculate the internal forces of the lining and strata separately under the premise of satisfying the deformation coordination conditions, and verify the stability of the strata and design the cross section of the members accordingly. Compared with the load structure method, the stratigraphic structure method fully considers the interaction between the underground structure and the surrounding strata, and can fully simulate the structural internal force of the underground structure and the surrounding strata in each construction working condition as well as the deformation of the surrounding strata, which is more in line with the engineering reality. However, the prerequisites for the application of the stratigraphic structure method are deep buried tunnels.

According to the Highway Tunnel Design Specification Book 1 Civil Engineering (JTG 3370.1-2018), the demarcation between shallow and deep buried tunnels is determined by the load equivalent height value and combined with geological conditions, construction methods and other factors. The formula for determining the equivalent height of the load is

$$H_p = (2 \sim 2.5)h_q \tag{1}$$

Where: H_p - shallow buried tunnel demarcation depth; h_q - load equivalent height, calculated according to the following formula.

$$h_q = \frac{q}{\gamma} \tag{2}$$

Where: q - vertical mean pressure in deep buried tunnels (kN/m2); γ - surrounding rock weight (kN/m3).

The Tunnel Regulations recommend that under mining method construction conditions, Class IV~VI enclosing rocks are taken

$$H_p = 2.5h_q \tag{3}$$

Class I~III surrounding rock is taken

$$H_p = 2h_q \tag{4}$$

The specific deep and shallow burial criteria are

(1) When the depth of burial > Hp, for deep buried tunnels, according to "Tunnel Regulations" 6.2.2 and Table 6.2.2-2 to calculate and determine the surrounding rock pressure.

(2) When hq < depth of burial < Hp, the tunnel is shallowly buried and the surrounding rock pressure is calculated according to Appendix D of the Tunnel Regulations

(3) When the burial depth $< h_q$, for ultra-shallow buried tunnel, according to the "Tunnel Regulations" Appendix D calculate the surrounding rock pressure

As determined by the above formula, the intersection of the existing highway tunnel and the new high-speed rail tunnel is a deeply buried tunnel, so the stratigraphic structure method can be used for calculation.

3.2. Computational Model

In order to analyze the deformation and stresses of the rock and tunnel structure starting from the natural state and through the whole process of the construction of the HSR tunnel, the numerical calculations were carried out as follows.

(1) Initial ground stress balance.

(2) Excavation and support of the left and right lines of existing highway tunnels.

(3) Excavation of new high speed railway tunnel by step method with composite support; according to the most unfavorable consideration, the length of step is 7m, the lagging distance of second lining is 160m, and the cross section is excavated by CRD method.

(4) Construction of high speed rail tunnel is completed.

The geotechnical finite-difference model is shown in Figure 3. The model is taken as 350m along the direction of the new high-speed railway tunnel and 320m along the direction of the existing highway tunnel, and the ground is established according to the actual undulation of the mountain. The finite difference position relationship model of the two tunnels is shown in Figure 4.

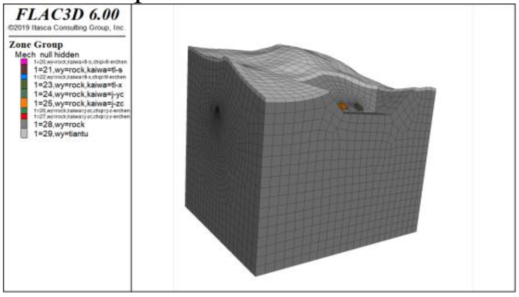


Figure 3: Geotechnical Finite Difference Calculation Model

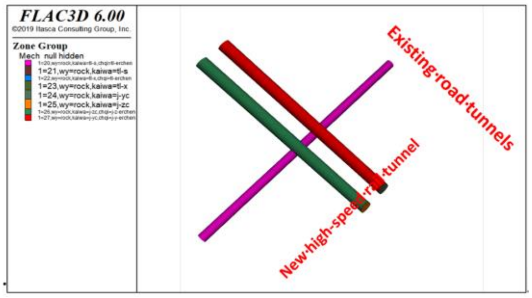


Figure 4: Tunnel Interposition Relationship

4. Basic Assumptions and Calculation Parameters

4.1. Basic Assumptions

The calculation makes the following basic assumptions in modeling and finite difference calculations.

(1) The geotechnical body is an isotropic, continuous elastic-plastic material, and the Mohr-Coulomb yield criterion is used for the plastic yield criterion of the material.

(2) The initial ground stress is considered only for gravity loading.

4.2. Calculation Parameters

The parameters were selected from the ground investigation data of this project, and some parameters were taken as conservative values according to the experience of previous projects and relevant specifications, taking into account the damage to the surrounding rock caused by blasting excavation of existing tunnels, the surrounding rock parameters were discounted by 0.8.

Considering the actual situation, the existing highway tunnel has been built and operated for many years, and the lining structure is partially aged, the secondary lining parameters of the existing highway tunnel are discounted by 0.7 strength according to C20 concrete, and the initial support parameters are discounted by 0.7 strength according to C20 concrete. The specific calculation parameters are shown in Table 1.

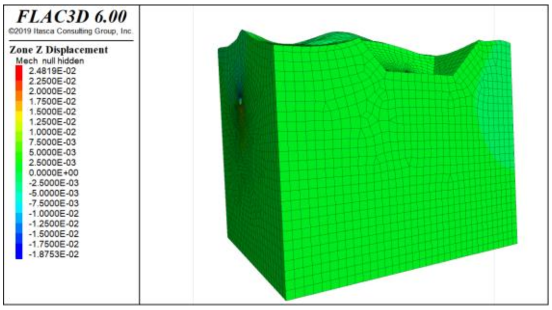
Table 1: Calculation parameters to take the value table

Materials	Ontological model	Modulus of elasticity/MPa	Allowable weight kN/m^3	Poisson's ratio	Cohesive force MPa	Friction angle	Saturated compressive strength
Fill	Moore Cullen	50	19.75	0.42	0.01	23	/
Rock	Moore Cullen	1.3×10^3	26	0.34	0.3	35	9.1
second lining	Flexibility	14×10^3	25	0.2	/	/	/
Primary Branch	Flexibility	14×10^3	22.5	0.2	/	/	/
set of arches	Flexibility	20×10^3	22.5	0.2			

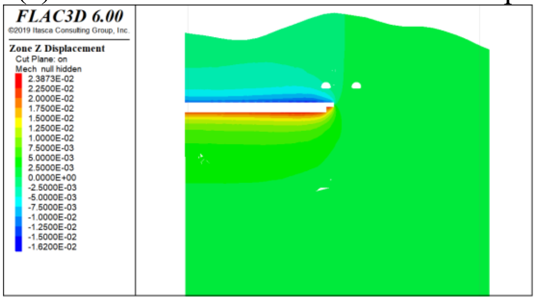
5. Analysis of Calculation Results

5.1. New High-speed Rail Tunnel Excavation to the Middle of the Left and Right Lines of the Existing Road Tunnel

When the new high-speed railway tunnel is excavated to the middle of the left and right lines of the existing highway tunnel, the vertical displacement of the surrounding rock, the distribution of the plastic zone of the surrounding rock, the X-axial displacement of the existing highway tunnel lining, the Y-axial displacement of the existing highway tunnel lining, and the distribution of the vertical displacement of the existing highway tunnel lining are shown in Figure 5-Figure 8.



(a) Three-dimensional distribution map



(b) Two-dimensional distribution map

Figure 5: Vertical displacement of surrounding rock

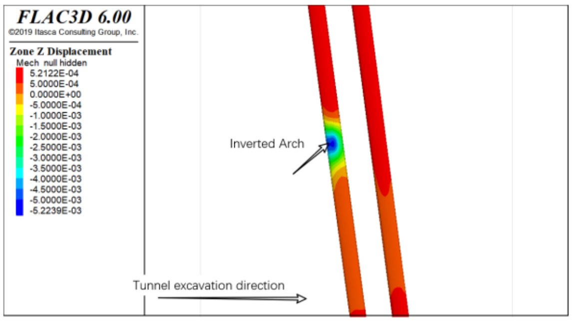


Figure 6: Vertical displacement of secondary lining of existing highway tunnel

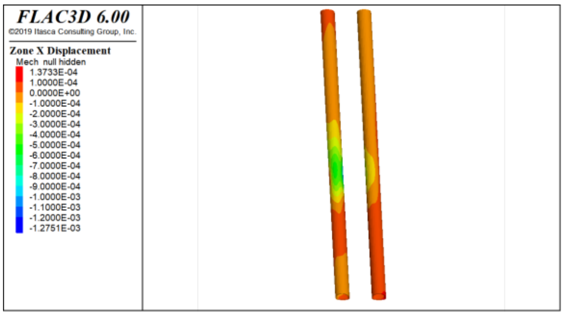


Figure 7: X-directional displacement of secondary lining of existing highway tunnel

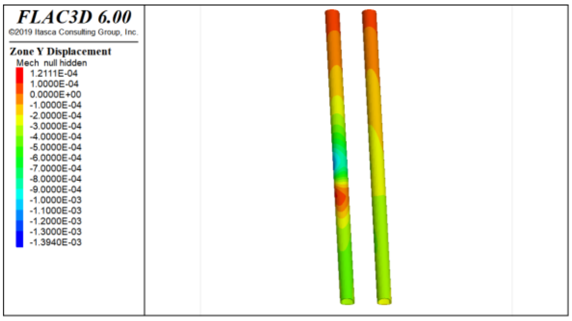


Figure 8: Y-direction displacement of secondary lining of existing road tunnel

From Figure 9, it can be seen that the new high-speed railway tunnel excavation to the middle of the left and right lines of the existing road tunnel, the new high-speed railway tunnel and the existing road tunnel intersection location occurs plastic zone through.

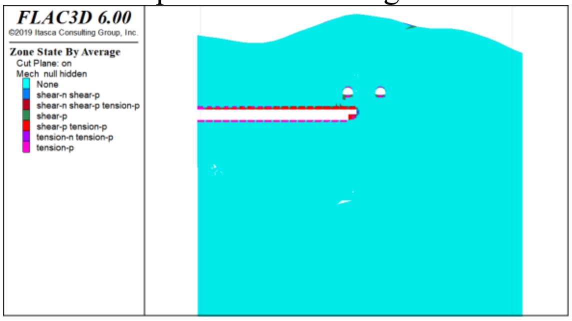


Figure 9: Distribution of plasticity zones

Extract the new high-speed railway tunnel excavation to the middle of the left and right lines of the existing highway tunnel, the surrounding rock displacement, the most unfavorable displacement of the existing highway tunnel lining structure as shown in Table 2.

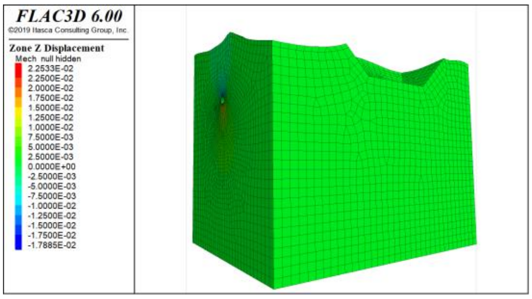
Table 2: Displacement of highway tunnel when new high speed rail tunnel is excavated to the middle of the left and right lines of the existing highway tunnel

Projects	Vertical displacement of surrounding rock/mm	Existing road tunnel lining structure displacement/mm		
		Vertical	X-axis	Y-axis
Just in time	24.82	0.51	0.14	0.12
Negative values	18.75	5.22	1.28	1.39

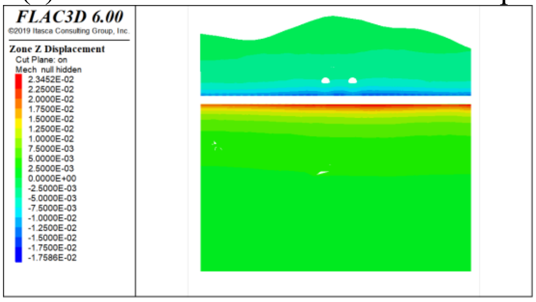
The maximum vertical displacement of the existing road tunnel lining structure is 5.22mm, the maximum X-axis displacement is 1.28mm and the maximum Y-axis displacement is 1.39mm.

4.2. Completion of the Construction of the New High-speed Railway Tunnel

When the excavation of the new high-speed railway tunnel is completed, the vertical displacement of the surrounding rock, the distribution of the plastic zone of the surrounding rock, the X-axial displacement of the existing highway tunnel lining, the Y-axial displacement of the existing highway tunnel lining, and the distribution of the vertical displacement of the existing highway tunnel lining are shown in Figure 10-Figure 13.



(a)Three-dimensional distribution map



(b) Two-dimensional distribution map

Figure 10: Vertical displacement of the surrounding rock

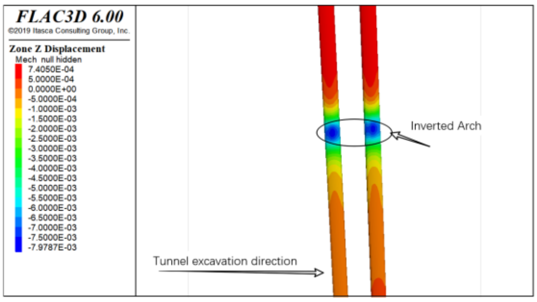


Figure 11: Vertical displacement of secondary lining of existing highway tunnel

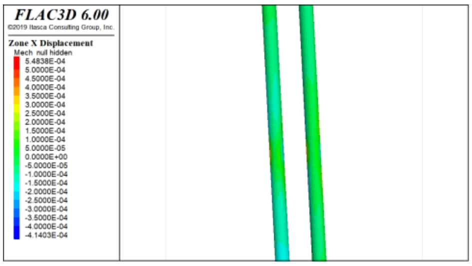


Figure 12: X-directional displacement of secondary lining of existing highway tunnel

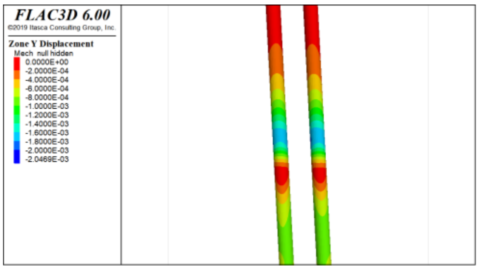


Figure 13: Y-direction displacement of secondary lining of existing road tunnel

As can be seen in Figure 14, when the new HSR tunnel is excavated to the right line of the existing highway tunnel, no plastic zone penetration occurs at the intersection of the new HSR tunnel and the existing highway tunnel.

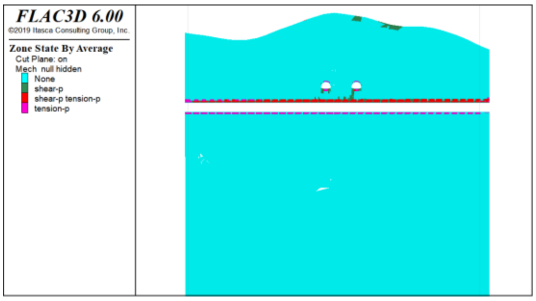


Figure 14: Distribution of plasticity zones

Extraction of the new high-speed railway tunnel excavation is completed, the surrounding rock displacement, the most unfavorable displacement of the existing highway tunnel lining structure is shown in Table 3.

Table 3: Displacement of road tunnels at the completion of excavation of new high-speed rail tunnels

Projects	Vertical displacement of surrounding rock/mm	Existing road tunnel lining structure displacement/mm		
		Vertical	X-axis	Y-axis
Just in time	22.53	0.74	0.55	0
Negative values	17.89	7.98	0.41	2.05

The maximum vertical displacement of the existing road tunnel lining structure is 7.98mm, the maximum X-axis displacement is 0.55mm and the maximum Y-axis displacement is 2.05mm.

6. Conclusion

In this paper, based on the new Xi'an-Chongqing high-speed railroad tunnel Xujiapo small clearances through the existing highway tunnel, using the stratigraphic structure method to analyze the impact of the new high-speed railroad tunnel small clearances through the existing highway tunnel on the safety of the existing highway tunnel structure, the main conclusions of the analysis are as follows.

(1) The new railroad tunnel under the existing highway tunnel excavation to the existing highway tunnel directly below the intersection of the location of the plastic zone penetration, the impact is large, the construction time should focus on strengthening the over-support protection.

(2) Underpass tunnel excavation causes the largest vertical displacement of the existing tunnel above, and the vertical displacement increases with the excavation of the new tunnel below.

(3) The maximum vertical displacement of the existing highway tunnel is 7.98mm, which is close to the requirement of 10mm warning value in the Technical Specification for Safety Protection of Urban Rail Transit Structure, and the safety risk is large.

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