Study on Deformation Characteristics of Surrounding Rock in Small Clearance Tunnel Excavation in Backfill Soil Layer

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Abstract. To solving the engineering problems of tunneling in backfill soils, the shallow buried concealed excavation section of the northern line of the Zengjiayan Bridge Tunnel Project in Chongqing has been taken as the relying project and numerical analysis and monitoring have been used to study on deformation characteristics of surrounding rock in small clearance tunnel excavation in backfill soil layer. The result of this study reveals that: firstly, during the excavation the maximum surface settlement will move from the top of the advance tunnel to the top of the intermediate rock pillar. Secondly, the surrounding rock deformation pattern of the backward tunnel could be described as: predeformation-sharp deformation- deformation convergence, and the surrounding rock deformation pattern of the advance tunnel could be described as: predeformation-sharp deformation- first deformation convergence- additional deformation- final deformation convergence. Thirdly, the excavation of the advance tunnel will lead to the predeformation in vault, arch and the side wall of the backward tunnel, and the excavation of the backward tunnel will lead to the additional deformation in the same places of the advance tunnel. The conclusion of this study is consistent with the existing research and can provide reference for similar projects.

Keywords: highway tunnel, backfill soil layer, surrounding rock deformation, small clearance tunnel.

1 Introduction

In the process of urbanization, many deep backfill soil areas have been formed in Chongqing. This phenomenon is caused by the way of cutting mountains and filling valleys in the early years of architecture construction. Influenced by the backfill history and backfill quality, the backfill soil tends to be loose, in a state of underconsolidation and in a stage of continuous settlement, which is a negative engineering geological condition. Nowadays, the construction of urban highway tunnels will inevitably

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penetrate the deep and long backfill soil area, which faces many engineering problems, such as unclear physical and mechanical properties of the ground, inexperienced parameter design, and great technical difficulties in construction.

Some scholars have studied the engineering properties of backfill soil layer, tunnel excavation methods and auxiliary reinforcement measures in backfill soil layer, and the deformation law of surrounding rock in small clearance tunnel excavation. Chandler[1] first found through the laboratory test that the strength of the backfill of the soil-rock mixture would be affected by the presence of large volume stone in the sample. Medley and Lindquist[2] proposed the concept of soil-rock threshold based on the stone content in soil and the surface profile and distribution characteristics of blocks. Through theoretical analysis, Hu Yayuan and Zhou Huanhui[3] proved that the consolidation characteristics of saturated massive mixed backfill were affected by pore permeability coefficient, pore permeability coefficient of massive soil and fluid exchange parameters. Chen[4] studied the stress and deformation characteristics of surrounding rock of a tunnel group excavated by using the reserved core earth method in the backfill soil layer through numerical simulation. Zuliang Zhong et al.[5] analyzed various causes of surface settlement caused by mechanized tunneling in the backfill soil layer of soil-rock mixture, and further optimized the excavation parameters. Wencong Qi et al.[6] analyzed the adaptability of TBM roadheader in soil-rock mixture formation. Bao Xiankai et al.[7] studied the excavation stability of long-span ultra-shallow underground tunnels with backfilled soil and revealed the stress distribution of surrounding rock during excavation. The study of Yu Shun et al.[8] proved that the use of CD method to excavate backfilled soil tunnels is conducive to reducing the excavation span and reducing the construction risk. Tang Jinshi [9] introduced the deformation mechanism of long span shallow buried tunnel under the subgrade and analyzed the deformation control technology of long span shallow buried subgrade backfill tunnel. Shiding Cao et al.[10] discussed a reasonable construction plan for the bifurcated tunnel, taking control of the deformation of the intermediate rock pillar as an entry point. Hongpeng Lai et al.[11] studied the deformation of surrounding rock of existing tunnels caused by close excavation of new tunnels under existing tunnels, and found that the excavation of new tunnels would cause vertical settlement and torsional deformation of existing tunnels.

This study relies on the northern line of Chongqing Zengjiayan Bridge Tunnel Project shallow buried concealed excavation section using monitoring and numerical analysis of the backfill soil layer of small clear distance tunneling deformation characteristics of the surrounding rock, the relevant conclusions can provide certain ideas and reference for similar projects.

2 Background of Engineering

The northern concealed section of the Zengjiayan Bridge Tunnel Project is part of the Chongqing Zengjiayan Jialing River Bridge Project. The difficulties of this tunnel project are as follows: firstly, the tunnel is a small clearance tunnel, and the clearance between the left and right tunnels is extremely small, the smallest clearance is only 1.5m, which is much smaller than the design reference value given by the relevant specification. Secondly, the burial depth of the tunnel is shallow, the minimum burial depth is only 20m. Thirdly, the surrounding rock of the tunnel is artificially backfilled, and the self-stability ability after excavation is quite poor, which is easy to cause large deformation. Finally, the tunnel construction site is located in the urban core and is surrounded by dense buildings, thus requiring strict control of surrounding rock deformation and surface settlement.

Tunnel rock backfill soil, backfill time is more than 10 years, fill soil is mainly the abandonment of earth and stone, block gravel content is high, the deep fill soil is not sorted and compacted, there may be a large pore space, its consolidation time is long. The surrounding rock is poor in self-stability, and it is easy to deform after excavation to form collapse or even roofing, causing uneven settlement of the upper surface. The results of the ground investigation revealed that the backfill soil surrounding rock at the site were of the following levels: IV3, V1 and V2. The mechanical parameters of the surrounding rock measured by field tests and indoor tests are shown in table 1.

Table 1. Mechanical parameters of the surrounding rock.

Level	Bulk Density $\gamma(kN/m^3)$	Young's modulus E(GPa)	Poisson's Ratio	Friction $\varphi(°)$	Cohesion c(MPa)
IV_3	23.0	0.0625	0.225	46.5	0.025
V_1	21.0	0.0415	0.250	40.0	0.014
V_2	18.5	0.0215	0.300	33.5	0.008

3 Surrounding Rock Deformation Monitoring

3.1 The method and items of monitoring

The object of this study is surrounding rock deformation, so monitoring items include surface settlement, settlement of vault, and horizontal displacement. According to “Technical Specifications for Construction of Highway Tunnel” (JTG/T 3660-2020), corresponding equipment that been used to tunnel monitoring are listed in table 2.

Table 2. Equipment used in tunnel monitoring.

Monitoring items	Equipment	Precision	Meaning of monitoring
Surface settlement Settlement of vault Horizontal displacement	Electronic Total Station	0.1mm	Quantitative evaluation of the stability of surrounding rock and initial support to provide data support for construction safety warning.

The specific monitoring method is as follows: using the electronic total station to measure the coordinates of the monitoring points around the tunnel and record the data by the surveyors, then write the recorded data into the surrounding rock monitoring and measurement calculation software for data processing and analysis, and provide real-time feedback on the results of the evaluation. Photographs of tunnel monitoring are shown in figure 1 and figure 2.

Fig. 1. Electronic Total Station.

Fig. 2. Surrounding rock deformation monitoring.

According to "Technical Specifications for Construction of Highway Tunnel" (JTG/T 3660-2020), the schematic diagram of monitoring points is shown in figure 3.

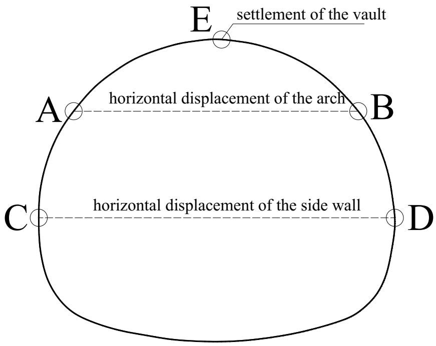

Fig. 3. The schematic diagram of monitoring points.

3.2 Analysis of monitoring results

The deformation of the surrounding rock at section YK0+430 of the tunnel was continuously monitored for 50 days and the results are shown in figure 4. From figure 4, the following conclusions can be drawn:

Firstly, surrounding rock of the advance tunnel deforms rapidly right after the excavation and converges gradually along with the excavation of the advance tunnel. Additional deformation of surrounding rock of the advance tunnel has been produced when the backward tunnel reaches at the location of the monitoring section and has converged gradually again with the excavation of the backward tunnel.

Secondly, the final converging time of all monitoring points' deformation of the advance tunnel is almost the same, is about the time that the tunnel face surpasses the monitoring section 75m. however, the primary converging time of different monitoring points is not quite the same. The converging speed of the side wall's horizontal displacement is much faster than the settlement of vault and the horizontal displacement of the arch.

Thirdly, final converging values of surrounding rock deformation of advance tunnel are as follows: settlement of vault-- 27.9mm, horizontal displacement of the arch-- 21.6mm, horizontal displacement of the side wall—42.0mm. Therefore, the advance tunnel may be damaged at the side wall and arch.

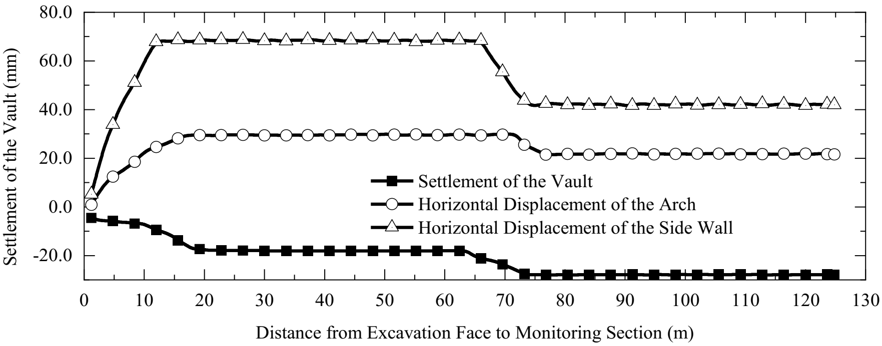

Fig. 4. Deformation monitoring results of section YK0+430.

4 Numerical analysis surrounding rock deformation

4.1 Model and parameters of numerical analysis

For analyzing the characteristics of surrounding rock deformation while tunneling in the backfill soil layer, the FLAC3D software has been used in this research, and the analysis model is shown in figure 5. the excavation span is 12.8m, the depth of the tunnel is 20m, and the clearance between the advance tunnel and the backward tunnel is 2m. According to relevant literatures and numerical analysis experience, the numerical analysis results are valid when the distance between the model boundary and the tunnel contour is 3~5 times greater than the tunnel width. Therefore, the size of the model is $X \times Y \times Z = 260m \times 60m \times 110.7m$. Displacement constraints in the X direction are applied to the left and right boundaries of the model, the front and back boundaries impose displacement constraints in the Y direction, and the bottom boundary imposes a displacement constraint in the Z direction.

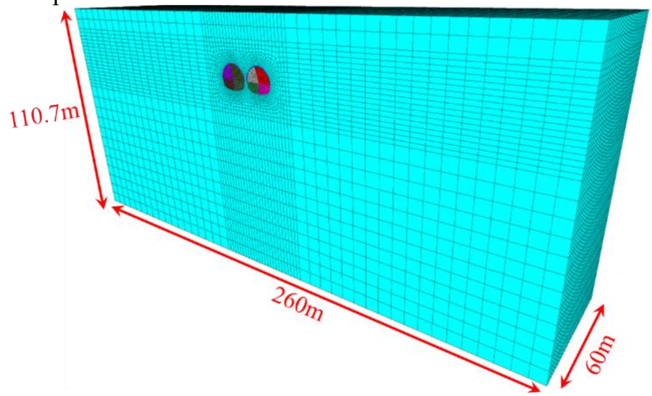

Fig. 5. Numerical analysis model.

According the actual excavation parameters of the tunnel, the excavation cycle footage is 1.2m, the distance between each excavation face is 3.6m, and distance between the advance tunnel and the backward tunnel is 60m. The center diagram method (CD method) has been used to excavate the tunnel and the specific construction process is shown in figure 6.

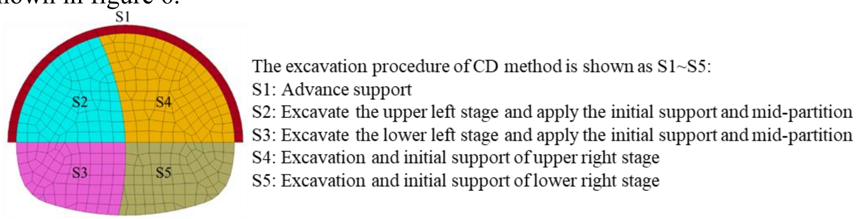

Fig. 6. Schematic drawing of tunnel construction process by using CD method.

In the numerical analysis, solid element simulation is used to simulate the surrounding rock and the leading pipe shed support. Mohr-Coulomb criterion is used for the surrounding rock constitutive model, and elastic criterion is used for the leading pipe shed constitutive relation. Shell element is used to simulate the initial support structure and temporary support structure. According to the New Austrian Tunnelling Method theory, after tunnel excavation, the surrounding rock and the primary support structure serve as the main body of load, and the lining only serves as the safety reserve. Therefore, only the primary support is considered in the numerical analysis process, and the lining is not.

The values of the mechanical parameters of surrounding rock in the numerical analysis are based on table 1, and the surrounding rock level is level V1. In the initial support structure, the bearing effect of the steel mesh is subtle, and the main function is to provide adhesion objects for the shotcrete, which is not considered in the numerical analysis. The function of the initial support steel frame is considered by the "replacement stiffness method", and the deformation resistance of the steel frame is converted to the shotcrete. The equivalent formula is shown in equation (1).

$$E = E_0 + A_g E_g / A_0 \tag{1}$$

In the formula above: E ——Elastic modulus of shotcrete after conversion.

E_0 ——Initial elastic modulus of concrete.

A_g ——Steel frame cross-sectional area.

E_g ——Elastic modulus of steel.

A_0 ——Concrete area.

In the numerical analysis, the effect of the bolt is considered by "cohesion equivalent", The equivalent formula is shown in equation (2).

$$c = c_0\left(1 + \frac{\eta}{9.8}\frac{\tau S_m}{ab} \times 10^4\right)$$

In the formula above: c ——Cohesion of bolting reinforcement zone of surrounding rock.

c_0 ——Initial cohesion of surrounding rock in reinforcement zone.
η ——Empirical coefficient with values from 2 to 5.
τ ——Maximum shear stress of bolt.

S_m ——bolt section area.
a ——Longitudinal spacing of bolts.
b ——Transverse spacing of bolts.

4.2 Analysis of numerical simulation results

4.2.1 Surface settlement analysis. Surface settlement curves in different stage of tunnel excavation is shown in figure 7. The following conclusions can be drawn from this figure:

Firstly, with the progress of excavation, the surface settlement gradually increases, and when the tunnel excavation is completed, the maximum surface settlement reaches 16.3mm.

Secondly, the surface settlement characteristics of tunnel excavation with small distance are significantly different from those of normal tunnel excavation. When the advance tunnel is excavated, the maximum surface settlement of each excavation stage appears right above the advance tunnel. When the backward tunnel is excavated to the analysis section, the maximum surface settlement begins to move from the right above the advance tunnel to the center line of the intermediate rock pillar. When the tunnel excavation is completed, the maximum surface settlement appears right above the intermediate rock pillar.

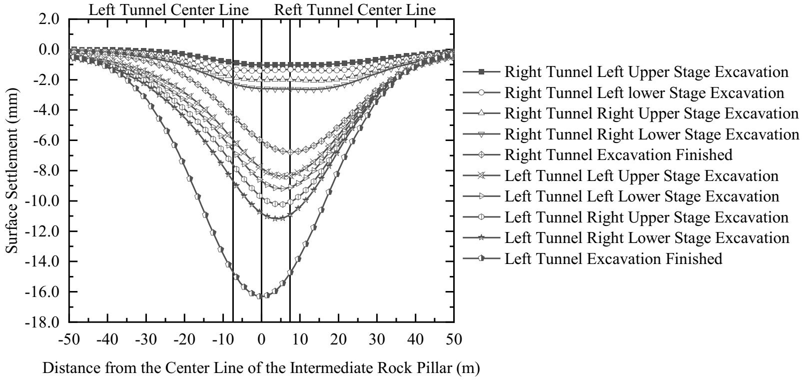

Fig. 7. Surface settlement curves in different stage of tunnel excavation.

4.2.2 Deformation around the tunnel contour analysis. Curves of deformation around the tunnel contour along with the excavation process are shown in figure 8~figure 11. The following conclusions can be drawn from those figures:

Firstly, the deformation pattern of the backward tunnel could be described as: predeformation-sharp deformation- deformation convergence, and the deformation pattern of the advance tunnel could be described as: predeformation- sharp deformation- first deformation convergence- additional deformation- final deformation convergence.

Secondly, In the excavation of small clearance tunnel, the interaction between the advance tunnel and the backward tunnel is obvious, but different parts are affected to different degrees. the excavation of the advance tunnel will lead to the predeformation in vault, arch and the side wall of the backward tunnel, and the excavation of the backward tunnel will lead to the additional deformation in the same places of the advance tunnel. However, for the inverted arch, the interaction between the advance tunnel and the backward tunnel excavation is not obvious.

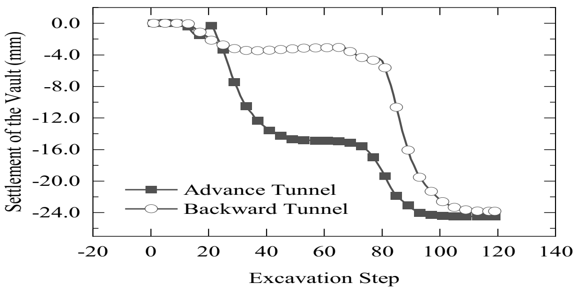

Fig. 8. Settlement of the vault

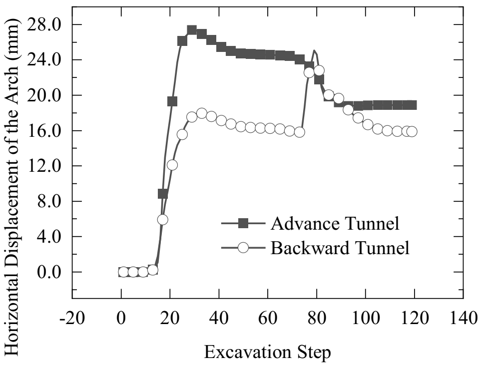

Fig. 9. Horizontal displacement of the arch.

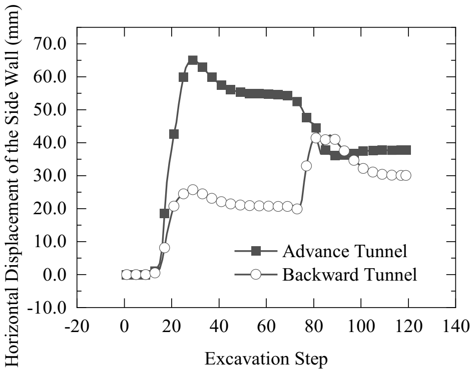

Fig. 10. Horizontal displacement of the side wall.

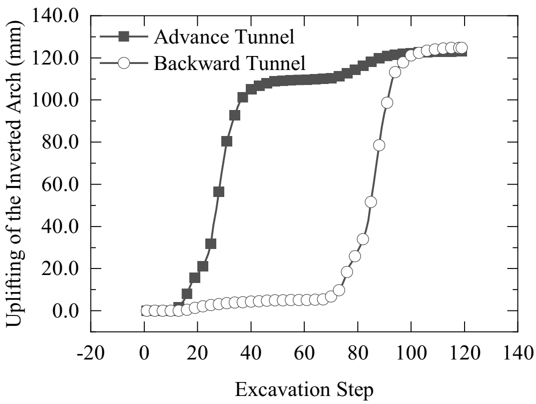

Fig. 11. Uplifting of the inverted arch.

4.3 Comparative analysis of numerical simulation and monitoring

The actual construction environment of the tunnel is very complex, but the model and boundary conditions of the numerical analysis are relatively simple, so the tunnel monitoring results are not completely consistent with the numerical analysis results. To verify the accuracy of numerical analysis, the results of numerical analysis and tunnel monitoring results are drawn as shown in figure 12 to figure 14. And the final convergence value of deformation in the numerical analysis results and tunnel monitoring results is extracted, and the error is solved based on this value and the statistics are shown in table 3. errors of the final convergence values of surrounding rock deformation are as follow: horizontal displacement of the arch is 12.5%, settlement of the vault is 12.3%, horizontal displacement of the side wall is 10.1%, and the comprehensive error is 11.6%. Therefore, the results of numerical analysis are close to tunnel monitoring values, and the boundary conditions and parameter selection of numerical analysis are valid.

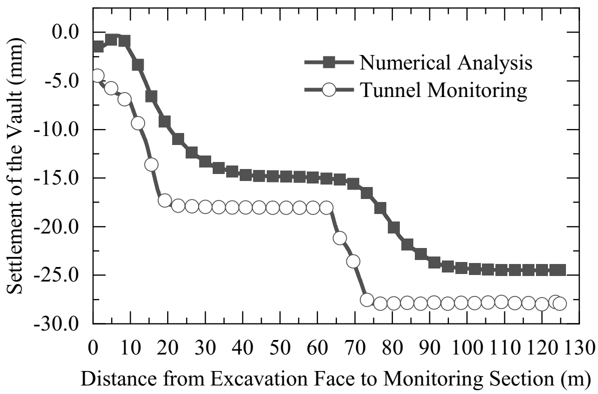

Fig. 12. Comparison of settlement of the vault.

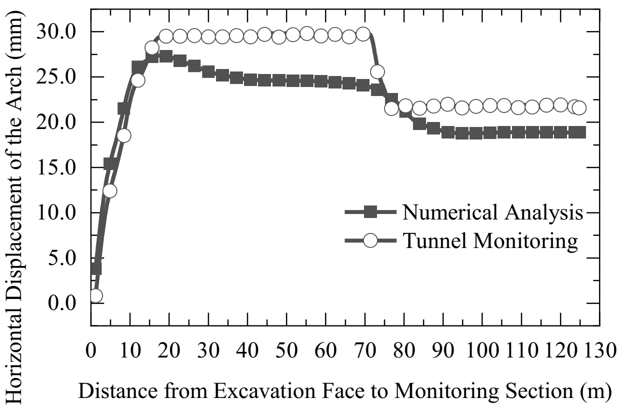

Fig. 13. Comparison of horizontal displacement of the arch.

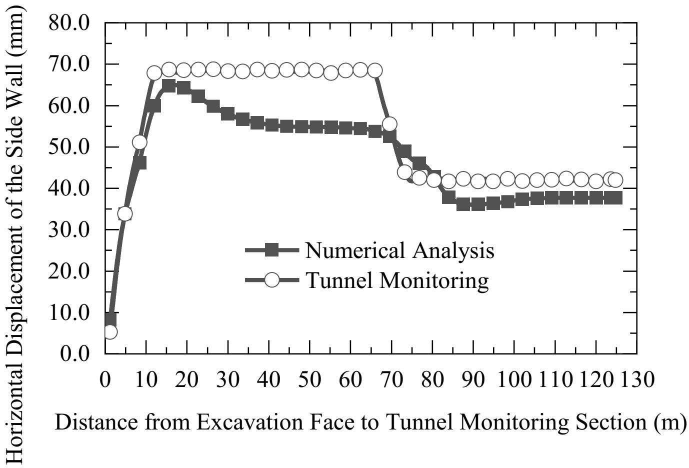

Fig. 14. Comparison of horizontal displacement of the side wall.

Table 3. Numerical analysis error statistics table.

Settlement of the vault			Horizontal displacement of the arch			Horizontal displacement of the side wall		
Calculated value (mm)	Measured value (mm)	Error (%)	Calculated value (mm)	Measured value (mm)	Error (%)	Calculated value (mm)	Measured value (mm)	Error (%)
24.5	27.9	12.3	18.9	21.6	12.5	37.7	42.0	10.1

5 Conclusion

Through this study, the following conclusions can be drawn:

Firstly, the surface settlement characteristics of small clearance tunnel excavation are significantly different from normal tunnels excavation. When the advance tunnel is excavated, the maximum surface settlement of each excavation stage appears right above the advance tunnel. When the backward tunnel is excavated to the analysis section, the maximum surface settlement begins to move from the right above the advance tunnel to the center line of the intermediate rock pillar. When the tunnel excavation is completed, the maximum surface settlement appears right above the intermediate rock pillar.

Secondly, the surrounding rock deformation pattern of the backward tunnel could be described as: predeformation-sharp deformation- deformation convergence, and the surrounding rock deformation pattern of the advance tunnel could be described as: predeformation- sharp deformation- first deformation convergence- additional deformation- final deformation convergence.

Thirdly, the excavation of the advance tunnel will lead to the predeformation in vault, arch and the side wall of the backward tunnel, and the excavation of the backward tunnel will lead to the additional deformation in the same places of the advance tunnel. For the inverted arch, the interaction between the advance tunnel and the backward tunnel excavation is not obvious.

The conclusion of this study is consistent with the existing research and can provide reference for similar projects.

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