Finite Element Analysis of Unsymmetrical Pressure Treatment of Shallow-Buried Tunnel with Half-road and Half-tunnel

Qian Zhang 1*, Jianping Su 2, Bin Liu 1

1Second engineering Co.Ltd of CCCC Fourth Highway Engineering CO., LTD., Beijing, 101149, China
2General contracting company of CCCC, Beijing, 100088, China.
*Corresponding author’s e-mail: bjx5126@163.com

Abstract. Taking the Sajin tunnel project of T26 contract section of Du (Yun) An (Shun) Highway as an example, this paper analyzes the difficult problem of unsymmetrical pressure construction of the tunnel. This paper puts forward a systematic treatment scheme of setting anti-slide pile as the main part, and compares and verifies the calculation model established by Midas SoilWorks software. The calculation results show that this method can effectively reduce the bending moment and deformation at the left arch waist of the tunnel. The minimum safety factor of the initial support structure of the tunnel is 1.36, which greatly reduces the construction risk. At the same time, the quality control of the treatment process of the project is analyzed, and the corresponding treatment suggestions are put forward, which can provide reference for similar highway tunnel engineering design and construction.

1. General situation of the engineering
The total length of contract section T26 of Du'an highway project is 13.46km, involving two tunnels, among which the Sajin tunnel is located between the Keibing village and the Sajin group of Limu village, Baisuo Town, Changshun County, Qiannan Prefecture, which is a separated short tunnel. The left line is 387m long, and the right line is 485m long. The line roughly crosses the ridge from northeast to southwest. The design elevation of the entrance is 1224m, and the elevation of the exit is 1237m. The engineering area belongs to the landform of structural denudation low and middle mountain, with ground elevation of 1160-1355m and relative elevation difference of 195m. The natural ground slope at the entrance is about 30°-40°, the slope is relatively steep, the terrain at the exit is slightly gentle, the natural ground slope is about 20°-30°, there is no road access at the entrance and exit of the tunnel, so the traffic is extremely inconvenient. The bottom layer of the tunnel site is the Middle Triassic Bianyang For. (T2b), in which the inlet is sandstone and its weathered residual slope (Qel+ dl) cohesive soil, and the outlet is limestone. The saturated compressive strength of moderately weathered sandstone is 30MPa, and that of moderately weathered limestone is 35MPa. Groundwater is not well developed, mainly pore water in the surface eluvium and fissure water and karst water in the weathering zone of bedrock. The amount of water is greatly affected by porosity, fissure development degree and season, which is prone to water and mud inrush. Therefore, waterproof and drainage measures shall be taken. The basic intensity of earthquake in the tunnel site is VI degree area.
2. Engineering technical difficulties
The main technical problems faced by the project are as follows: 1) the phenomenon of tunnel shallow burying is serious, the maximum buried depth of the tunnel is 195m; 2) the water seepage of the tunnel is large, and the local rainy season happens, and the dripping water of the tunnel is relatively serious; 3) the unsymmetrical pressure effect of the tunnel is serious. The subgrade at the entrance of the tunnel is designed as half-road and half-tunnel. The left side is subgrade and the right side is tunnel. There is a part of mountain on the left side of the junction. The vertical cover is thin and the unsymmetrical pressure in the horizontal direction is large.

On September 11, 2018, according to the monitoring results, the tunnel monitoring unit issued the tunnel engineering danger warning (see Fig.1). At the same time, the surface and intercepting ditch of the tunnel cracked, and the water seepage of the right tunnel increased significantly. During the inspection of the tunnel, it was found that some of the initial support steel arches (three trusses) showed "S" type yield deformation at the arch line position, and the shotcrete collapsed in a large area, as shown in Fig.2. Further inspection showed that the initial support from the cave’s entrance to K159 + 540 section was deformed to varying degrees. The project is faced with serious construction risks, which need to be treated systematically to ensure the safety of subsequent projects.

![Accumulated displacement diagram of a section](image)

**Fig.1** Accumulated displacement diagram of a section

![Actual photos of structural risk early warning](image)

(a) Yield distortion of I-steel  (b) Cracking of the initial support

**Fig.2** Actual photos of structural risk early warning

3 Analysis of the original design scheme
3.1 Original design scheme of right line entrance of Sajin tunnel
The original design of K159 + 509 - K159 + 629 section at the right line entrance of Sajin tunnel adopts S-Va type support, I20b type steel frame, with a spacing of 60cm, 26cm thick C25 shotcrete and 50cm thick C30 reinforced concrete secondary lining. The design and construction plan is to reserve core soil method for circular excavation.
3.2 Numerical simulation analysis of the scheme  
For the original design scheme and the proposed comparison scheme, the calculation model is established by Midas SoilWorks software for comparison and verification, and the calculation parameters are shown in Table 1. According to the characteristics of the tunnel, the typical section of K159 + 540 with steep terrain at the entrance of Sajin tunnel is selected as the representative. The surrounding rock is mainly class V surrounding rock. According to the rock classification, the tunnel finite element model is established to simulate the numerical calculation and analysis of the influence of tunnel excavation, as shown in Fig. 3.

Table 1 Summary of geotechnical unit calculation parameters value

| Unit name          | Silty clay layer | Highly weathered sandstone | Intermediary weathered sandstone | Advance reinforcement body | Anti slide pile | Initial support |
|--------------------|-----------------|---------------------------|----------------------------------|---------------------------|----------------|----------------|
| Attribute type     | Plane           |                           |                                   |                           |                |                |
| Constitutive model type |                |                           |                                   |                           |                |                |
| Modulus of elasticity E (MPa) | 110.18 | 200 | 1030 | 350 | 29791 | 27800 |
| Poisson's ratio Nu | 0.29 | 0.34 | 0.27 | 0.3 | 0.2 | 0.22 |
| Bulk density       | Gamma kN/m³     | 19 | 20.8 | 22 | 22 | 25 | 25 |
|                    | Saturated kN/m³ | 19.5 | 21.8 | 23 | 23 | 25 | 25 |

Fig .3 Finite element model and calculation results of the original design scheme

Table 2 Calculation results of initial support of composite lining

| Position          | Unit number | Bending moment (N*m) | Axial force (N) | Eccentric moment (m) | Safety factor |
|-------------------|-------------|----------------------|-----------------|----------------------|---------------|
| Vault             | 3960        | 201892.28            | 1407407.35      | 0.143                | 2.15          |
| Left arch waist   | 3969        | 480324.43            | 2783011.96      | 0.173                | 0.89          |
| Right arch waist  | 3950        | 222230.80            | 1603966.38      | 0.139                | 1.95          |
| Left arch foot    | 3976        | 376194.25            | 833529.83       | 0.451                | 0.86          |
| Right arch foot   | 3993        | 251402.09            | 1774659.30      | 0.141                | 1.73          |
| Inverted arch     | 3983        | 18962.29             | 1136001.69      | 0.017                | 5.49          |
As shown in Table 2, it can be seen from the numerical analysis results that the maximum settlement of the vault is 42.2mm when the right line tunnel is excavated to the upper stage, which is slightly smaller than the current K159 + 540 section monitoring the vault settlement of 68mm. It can be seen that the selection of model parameters is basically in line with the actual situation on site. After the completion of the tunnel excavation and the construction of the slope excavation retaining wall, the final vault settlement is 104mm, and the horizontal displacement of the wall top is 29.5mm. At this time, the most unfavorable position of the initial support structure of the right line is the position of the left arch waist, with the largest bending moment, which is also consistent with the current situation of deformation and distortion of the steel arch frame of the left arch waist of the initial support on site. The minimum safety factor at the left arch waist is less than 1, which is in an unstable state, prone to deformation and instability of the initial support structure, and the construction risk is large.

4. Scheme analysis of setting up anti slide pile

4.1 Finite element calculation and analysis

According to the deformation data in the tunnel and the displacement of the layout point of the tunnel top, in order to ensure the stability of the left line slope and reduce the influence of the excavation of the left line foundation on the secondary disturbance of the surrounding rock of the hidden tunnel of the right line tunnel, 1.8m × 2.4m anti slide piles are set radially at 5.6m on the left side of the design line within the range of ZK159 + 511-ZK159 + 541, the distance between the piles is 6m along the road direction, a total of 6 piles are set, the length of which is 18-22m, and the deviation angle of the pile body along the line direction is 15°, as shown in Fig. 4.

![Fig.4 Arrangement diagram of anti slide pile](image)

4.2 Finite element calculation based on anti slide pile scheme

![Fig.5 Horizontal displacement after setting up anti slide pile scheme](image)
Table 3 Calculation results of safety factor for initial support of composite lining

| Position        | Unit number | Bending moment (N•m) | Axial force (N) | Eccentric moment (m) | Safety factor |
|-----------------|-------------|----------------------|-----------------|----------------------|--------------|
| Vault           | 3576        | 73283.94             | 1385206.23      | 0.053                | 3.50         |
| Left arch waist| 3586        | 295340.22            | 2580697.24      | 0.114                | 1.36         |
| Right arch waist| 3565       | 85669.26             | 1748746.05      | 0.050                | 2.24         |
| Left arch foot | 3613        | 142948.02            | 910514.90       | 0.157                | 3.02         |
| Right arch foot| 3608        | 180527.12            | 1469118.11      | 0.123                | 2.31         |
| Inverted arch  | 3621        | 6521.90              | 1025624.92      | 0.006                | 6.62         |

As shown in Fig. 5 and Table 3 of calculation results, the final settlement of vault is 74mm and the horizontal displacement of wall top is 19.2mm after the completion of tunnel excavation and the construction of retaining wall for slope excavation. At this time, the most unfavorable position of the right line initial support structure is still the position of the left arch waist, with the largest bending moment, but at this time, the minimum safety factor at the left arch waist increases to 1.36, the initial support structure is basically in a stable state, and the construction risk is effectively controlled. It can be seen that the bending moment and axial force of the initial support of the tunnel are small, the safety of the initial support is greatly improved, the scope of the plastic zone is also smaller, the horizontal displacement and vertical displacement are significantly reduced, so it can be seen that the anti slide pile has the most obvious effect on the unsymmetrical pressure of the right tunnel.

4.3 Construction treatment suggestions

For this shallow-buried and unsymmetrical pressure tunnel with half-road and half-tunnel, the treatment suggestions are as follows:

1. The section with the most serious deformation is provided with arch protection, and I20b I-steal is used for secondary support, 1 truss with a spacing of 1m; the circumferential spacing is 1.2m, with grouting and strengthening support; the mountain surface is provided with observation piles, and the deformation is regularly observed;

2. According to the deformation data in the tunnel and the displacement of the layout point of the tunnel top, in order to ensure the stability of the left line slope and reduce the influence of the excavation of the left line foundation on the secondary disturbance of the surrounding rock of the right line tunnel, anti slide piles are set based on the calculation results;

3. According to the follow-up monitoring results of the deformation in the tunnel and the hillside of the tunnel top, the surface pre grouting combined reinforcement measures can be added in the follow-up.

5. Conclusion

In summary, under the influence of temperature, the box girder will produce an uneven vertical displacement of lateral and longitudinal distribution, and the difference of deflection is close to 2cm, which should cause design and construction attention and be given full consideration.

1. When the box girder is near the central axis of the bridge, the deflection is small, and the deflection towards the sides increases. A large range of camber occurs near the mid-span of the first span, with a maximum height of 4 mm.

2. There is a certain hysteresis effect on the deformation of the whole structure under high temperature, and the deformation value is relatively small, which has little effect on the overall structure safety.
(3) Using the Midas SoilWorks finite element software to establish an analytical model is conducive to better simulation of the actual site. The calculation results are in good agreement with the measured results.

References

[1] Huang M L, Meng X W, Tan Z S. Research on the Blasting Shock Absorption Technology of Shallow-Buried Tunnel Under-Traversing the Dense Houses. Advanced Materials Research, 2011, 243-249:3546-3550.

[2] JIN Xue-yang, LI Zong-li. Numerical simulation of excavation of loess shallow-buried tunnel. Journal of Northwest A & F University, 2009, 37(5):224-228.

[3] Lu, Lifang, Liang, Shasha, Luo, Shaoyun. Optimization of the Construction Technology of Shallow-Buried Tunnel Entrance Constructed in Residual Slope Accumulation of Gravelly Soil. Geotechnical & Geological Engineering, 2018.

[4] Huang, Ming Li, Chen, Ke Zhi, Tan, Zhong Sheng. Study on Surrounding Rock Deformation Discipline of Extra-Large Section Super-Shallow-Buried Tunnel. Applied Mechanics & Materials, 90-93:2318-2322.

[5] YU Jun. Study on Construction Scheme Optimization of Shallow-buried Tunnel undercrossing Existing Metro Station with Zero-clearance. Tunnel Construction, 2013.

[6] LIU Yingqi, ZHANG Xiedong, LI Jiali. Study of Rock Stress Release Rate in Shallow-buried Tunnel Based on Displacement-Back-Analysis. Journal of Wuhan University of Technology, 2015.

[7] LI Yong-suo, ZHANG Ke-neng, HUANG Chang-bo. Analysis of stability of shallow-buried tunnel built by pipe-roof pre-construction method. Journal of Central South University, 2012, 43(9):3646-3651.