Stability analysis of Jiguanshan Tunnel construction under karst tiankeng

Fei Wan¹*, Xuan Zhang¹, Tangjun Li²

¹Bridge and Tunnel Research center, Research Institute of Highway Ministry of Transport, Beijing, China
²The Fourth Engineering Co., Ltd. of CCCC First Highway Engineering Co., Ltd, Nanning, China

*Corresponding author: haoqinyuan21@t5y.cn

Abstract. The overlying rock mass under the tiankeng develops karst and thus has poor mechanical properties, which brings about great risks for the tunnel undercrossing construction. In order to determine the safety conditions of the tunnel and karst tiankeng during the undercrossing construction of the Jiguanshan Tunnel, a three-dimensional elastoplastic numerical model was established to analyze the deformation laws of the surrounding, deep and surface rock mass. The calculation results showed that the deformation of surrounding rock was dominated by settlement. With the longitudinal deformation of 57.3mm, the stability of the tunnel face was poor and the surrounding rock of the arch was prone to instability. The deformation of the surface tiankeng was slight. However, given that the uncertainty of karst development at the bottom of the karst tiankeng and the influence of tunnel construction blasting vibration, the surface rock was still at high risk of instability. The research results can provide references for the design of similar projects.

1. Introduction

Tiankeng is a special and grand negative surface terrain in the karst area. In terms of the spatial and morphological characteristics, it has a huge volume, steep and trapped rock wall and deep well-shaped or barrel-shaped outline. It often develops in the soluble rock layer (mainly carbonate rock) with extremely large continuous deposition thickness and aquifer zone thickness. The plane width and depth are more than 100m, and the bottom is connected with the underground river [1-3]. The karst tiankeng is the result of the long-term combined effects of karst groundwater system on the chemical dissolution of carbonates, mechanical erosion, gravitational collapse and water transport. The tiankeng bottom passages and cracks are developed, and thus the overlying rock mass under the tiankeng has poor mechanical properties. Disturbing the surrounding rock during the construction of the tunnel underneath the tiankeng can easily cause the tiankeng to lose stability and threaten the safety of tunnel construction.

The Jiguanshan Tunnel is a two-way and separated six-lane highway tunnel. The left-line tunnel is 3772m long and the right-line tunnel is 3800m long. It is located in Lexi Village, Lushan Town, Weining County, Guizhou Province, crossing the Zhongshan Watershed between Lexi and Qinggou. The tunnel site is in the structural dissolution peak cluster depression landform area where the peak cluster bases are connected, the karst hills and depressions are distributed alternately, and the karst landforms such as
dissolution funnels and sinkholes are developed. A karst tiankeng is developed directly above the K72+220-K72+340 section of the Jiguanshan Tunnel (see Figure 1), and the base of the tiankeng is 76 m away from the tunnel vault. The tiankeng has surface water collected all year round, and there is a sinkhole to discharge water. It had found that the tiankeng did not accumulate water in the course of the tunnel gushing, and all water was drained downward through the sinkhole.

![Aerial photo of tiankeng.](image1)
![Vertical view of tiankeng.](image2)

**Figure 1. Karst tiankeng.**

The route area of the Jiguanshan Tunnel is located in the subtropical monsoon humid climate zone. The precipitation is mostly concentrated in May to October, and the maximum daily precipitation is 166mm. The grade of the surrounding rocks of the left and right tunnels of the K72+220-K72+340 section is V. This section is located near the F47 fault zone and the contact zone between soluble and non-soluble rocks. The surrounding rocks of the tunnel are mudstone, sandstone and carbonaceous shale. It is composed of rock interspersed with coal seam, which is very soft rock. The construction of the K72+220-K72+340 section of the tunnel adopts the ring cut method. The excavation cycle takes about 1 steel frame spacing. The initial support adopts 3.5mφ25 hollow grouting anchor rod, I18 steel frame @60cm and 24cm C20 shotcrete. The construction of the Jiguanshan Tunnel underneath the karst tiankeng is prone to safety accidents. It is necessary to analyze the stability of the tunnel during the undercrossing construction to guide the design of the special construction plan of the tunnel.

2. Establishment of calculation model

2.1. Grid of model

The three-dimensional model was established for calculation. Taking into account the influence of the tunnel excavation on the initial in-situ stress of the surrounding rock, the left and right boundaries of the model are about 3 times the tunnel diameter from the tunnel center line, and the bottom boundary is about 3 times the tunnel diameter in order to reduce its influence. The distance from the bottom of the tunnel to the bottom boundary is considered as 4 times the tunnel height [4]. The horizontal width of the established three-dimensional model equals to the outer contour of the tunnel plus 35 meters from both sides and the longitudinal length is 30 meters. The established 3D model and tunnel model are shown in Figure 2.
2.2. Calculation parameters and boundaries

The surrounding rock of the Jiguanshan Tunnel ZK72+220-ZK72+340 undercrossing the karst tiankeng section is grade V. According to the geological survey report and construction design drawings, the physical and mechanical parameters of the surrounding rock and the initial supporting structure are shown in 1. The rock mass can be seen as an isotropic elastoplastic body, hence the Moore Coulomb model [5] is applicable here. The elastic model is used for the supporting structure analysis. In order to ensure similar physical and mechanical parameters with those of the actual engineering, the simulation of the bolt is considered in accordance with the principle of equivalence, that is, with the method of improving the cohesive force and internal friction angle $\phi$ value of the reinforced surrounding rock [6]. The physical and mechanical parameters of the initial support are also calculated according to the principle of equivalent stiffness (according to formula (1)), which is derived from the physical and mechanical parameters of steel arches, steel mesh and shotcrete, as shown in Table 6.35. The initial support density is calculated based on the same mass and no change in volume, and the Poisson ratio is taken as the shotcrete Poisson ratio.

$$E_q = E_c + A_{gg}E_{gg}/A_j' + A_{gw}E_{gw}/A_j'$$  \hspace{1cm} (1)

Where $E_c$ is the modulus of elasticity of shotcrete; $E_{gg}$ is the modulus of elasticity of steel arches; $A_{gg}$ is the cross-sectional area of the steel arch within the distance between the centers of adjacent steel arches; $A_j'$ is the cross-sectional area of the structure within the distance between the centers of adjacent steel arches; $E_{gw}$ is the elastic modulus of the steel mesh; $A_{gw}$ is the effective area of the steel mesh within the distance between the centers of adjacent steel arches.

| Item                     | Volumetric weight $\gamma$/ (kN/m$^3$) | Modulus of elasticity E/GPa | Poisson ratio $\mu$ | Cohesive force C/MPa | Internal friction angle $\phi$/° |
|--------------------------|----------------------------------------|----------------------------|---------------------|-----------------------|---------------------------------|
| Surface regolith         | 15                                     | 0.5                        | 0.45                | 0.05                  | 18                              |
| V grade surrounding rock | 18                                     | 1.5                        | 0.35                | 0.1                   | 23                              |
| Crushed zone             | 17                                     | 1.0                        | 0.45                | 0.05                  | 20                              |
| Reinforced surrounding rock | 19                                | 2.5                        | 0.35                | 0.2                   | 25                              |
| Initial support          | 26                                     | 30                         | 0.18                | /                     | /                               |

Model constraints: free upper surface, horizontal constraints on both sides, vertical horizontal constraints on both ends of the longitudinal direction, and vertical constraints on the bottom surface.
2.3. Layout of the monitoring points
The purpose of this calculation is to analyze the stability of the tunnel and karst tiankeng during tunnel construction. The stability analysis indices were the deformation of the surrounding rock and surface tiankeng at monitoring points during the tunnel construction process. In order to minimize the influence of boundary conditions on the calculation results, the cross section at the middle section of the model (about 35m) was selected as the research section. The monitoring points were set in the research section to track the settlement of the vault, the horizontal convergence of the spandrel, the surface settlement and the horizontal displacement of the rock mass. The layout of tunnel monitoring points is shown in Figure 3.

![Figure 3. The layout of monitoring point in the tunnel.](image)

3. Results
Four working conditions were selected for analysis, among which working condition 1 is the annular pilot pit passing through the research section, working condition 2 is the core soil passing through the research section, working condition 3 is the lower step through the research section, and working condition 4 is the cut-through of tunnel.

3.1. Vault settlement
The vault settlement curve of tunnel surrounding rock is presented in Fig.4.

![Figure 4. The vault settlement curve of initial support.](image)
As can be seen in Fig.4:
(1) the advanced settlement ratio before the tunnel face reaches is 58%, which decreases to 32.9% during excavation and to 9.1% after the section is closed. It can be seen that the settlement increment is small after the section is closed, and therefore the section should be closed as soon as possible.
(2) The settlement of surrounding rock at the studied section tends to be stable at 6.0m from the lower working face, the convergence distance is about 1D, and the final settlement of the surrounding rock vault is -36.6mm.
(3) The settlement increment caused by condition 1 accounts for 17.1% of the total settlement, and that caused by the three excavation steps 13-15 (condition 1) accounts for 41.2%. Special attention should be paid to the construction quality of advanced support during construction.

3.2. Horizontal convergence analysis
The horizontal convergence of the surrounding rock is shown in Fig.5.

![Figure 5. Convergence curve of initial support.](image)

It can be seen in Fig.5:
(1) the horizontal displacement value is small, the final value of the horizontal displacement at the arch springing is -10.2 mm, and that at the middle of the side wall is -21.9 mm.
(2) The horizontal convergence of the research section and the lower side line tends to be stable when the distance from the lower step working face is 6.0 m, and the convergence distance is about 0.5 D.
(3) The spatial variation characteristics of the horizontal convergence curve are as follows: ① as the tunnel face approaches, the displacement direction changes from pointing outside the tunnel to pointing inside the tunnel; ② the process of excavation from the upper step to the research section and the process to the lower step to the research section are the horizontal convergence acceleration stage towards inside of the tunnel; ③ after the section is closed, the horizontal convergence decreases, the displacement points to the outside of the tunnel, and stabilizes after a certain distance from the tunnel face.

3.3. The law of horizontal displacement of rock mass
In order to understand the horizontal displacement law of the rock mass in front of the tunnel face with the tunnel excavation process, the lateral displacement of the section from the surface node to the vault node is extracted and studied. The settlement duration curves of the surface settlement measurement points are shown in Figure 6.
It can be seen in Fig.6:

(1) When the tunnel face has not extended to the research section, and the distance is greater than 6.75m, the horizontal displacement of the monitoring point outside the tunnel excavation contour is larger as it is closer to the ground surface while it is smaller as it is closer to the vault. It shows that the advanced influence range of the tunnel face is expressed to the maximum on the ground. That is to say, when the tunnel is excavated, the front surface is first affected and the horizontal displacement is the largest.

(2) The horizontal displacement value of the monitoring point within the tunnel excavation contour area increases with the decrease of the distance from the tunnel face. The horizontal displacement of the monitoring point changes significantly when the annular drift heading is excavated at a distance of 2.5m from the research section.

(3) The horizontal displacement of the monitoring points outside the excavation contour is extremely small, and the maximum is 3.3mm. The horizontal displacement of the monitoring points within the tunnel excavation contour is much larger than the monitoring points outside the excavation contour, and the horizontal displacement of each monitoring point on the tunnel face is the largest It is 57.3mm, which appears within the outline of the core soil, indicating the necessity of retaining the core soil.

(4) The displacement of the monitoring points outside the tunnel excavation contour is dominated by settlement while the displacement of the monitoring points inside the tunnel excavation contour is dominated by horizontal displacement. During tunnel construction, the surrounding rock of the arch is easy to lose stability, and the settlement and deformation of the rock mass of the tunnel arch should be controlled in advance.

3.4. The law of surface settlement
In order to understand the settlement law of surface karst tiankeng during tunnel excavation, the vertical displacement of the surface of the study section was investigated. There are 15 monitoring points (Figure 7). The settlement curves of the surface settlement measurement points are shown in Figure 8.

![Figure 6. Horizontal displacement curves at various monitoring point.](image)

![Figure 7. The layout of the surface settlement monitoring points.](image)
It can be seen from Figure 8:

(1) The settlement values of the monitoring points all increase with the advancement of the tunnel face, and tend to be stable when the distance from the lower step working face is 6.0m.

(2) The settlement before the tunnel face reaches the research section accounts for about 52.0% of the total settlement, the settlement caused by step excavation accounts for about 22.6% and the settlement after the tunnel is closed accounts for about 25.4%, indicating that the advanced settlement and the settlement after closure are the key of surface settlement control.

(3) The lateral impact range of tunnel excavation is mainly 1.5B (B is the span of tunnel excavation). The surface settlement at 1.5B is about 16.7% of that of the midline. The secondary impact range is from 1.5B to 3B, and the surface settlement at 3B is about 6.7% of that of the midline. Due to topography, the maximum settlement point is on the side of the tunnel axis, and the maximum surface settlement is -2.9mm.

In summary, after the construction of the tunnel underneath the karst Tiankeng section, the maximum settlement deformation of the tunnel surrounding rock is -36.6mm, and the maximum horizontal convergence deformation is 21.9mm. The settlement is the main deformation form of surrounding rock of the tunnel. The horizontal displacement of the surrounding rock of the tunnel face is much larger than the that of the surrounding rock outside the excavation contour. The maximum horizontal displacement is 57.3mm. The maximum surface settlement is -2.9mm, and the surface settlement before the tunnel face reaches the research section accounts for about 52.0% of the total settlement.

4. Conclusions
Through the numerical calculation of the construction process of the Jiguanshan Tunnel under crossing the karst Tiankeng, the following main conclusions are obtained after comprehensive analysis:

(1) During the construction of the tunnel underneath the karst Tiankeng section, the stability of the tunnel face is poor, and the instability of surrounding rock of the arch is prone to occur.

(2) The deformation of the surface karst Tiankeng caused by tunnel construction is small, but considering the uncertainty of karst development at the bottom of karst Tiankeng and the influence of tunnel construction blasting vibration, tunnel construction may still cause disasters such as side wall slippage in karst Tiankeng, cracking and collapse of the bottom of the Tiankeng. Monitoring points should be set up at key locations of the karst Tiankeng for monitoring during the construction process.

(3) Surrounding rock deformation and surface karst Tiankeng deformation mainly occur in the advanced impact stage of tunnel face excavation. During tunnel construction, the advanced deformation of surrounding rock should be controlled and advanced support should be strengthened.

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