Numerical Analysis on Excavation Stability of Primary Support Arch-cover Method

Wei Li¹ *, Kexian Li² and Shijie Zhang³

¹ Research Center of Geotechnical and Structural Engineering, Shandong University, Jinan 250061, China
² Qingdao Metro Group Corporation, Qingdao, Shandong 266000, China
³ China Railway Academy Co., Ltd Chengdu Sichuan 611731, China

*Corresponding author e-mail: liwei9890816@163.com

Abstract. The primary support arch-cover method is a construction excavation that can effectively deal with upper soft and lower hard strata, but its deformation sensitivity is relatively large in shallow buried strata, and there are still problems in applicability when it occurred to large spans. This paper takes a hidden excavation station in Qingdao as the research background, and uses FLAC-3D simulation software to carry out numerical simulation calculations for the entire excavation of the primary support arch-cover method. The study analyzes the changes in stress and displacement of surrounding rocks under different excavation procedures. The results show that the excavation of the middle diversion tunnel is the process where the stress of the surrounding rock changes the most; the maximum stress and displacement of the rock and soil in the upper part of the station cavern happens when the arch structure is excavated; the surrounding rock remains basically unchanged during the excavation of the lower section. The safety and stability of the excavation process indicates that the method can be applied to metro stations in shallow buried hard rocks, providing a certain reference for similar projects.

1. Introduction

The primary supporting arch method transfers the load on the upper part of the arch to the surrounding rock through the arch foot, making full use of the capacity of the surrounding rock to carry, which is a widely adopted method for underground excavation of urban metro stations. However, due to higher requirements for the bearing capacity of surrounding rocks, there is room for discussion on its applicability in special strata. In order to meet the requirements of different strata, the two-line arch cover method, such as the primary support arch cover method, came out one after another. Scholars have also carried out detailed research on the applicable characteristics and mechanical mechanisms of different arch cover methods.

Jia [1] introduced the construction technology and control points of the arch cover method in detail, and described the advantages of the arch cover method compared with other construction technologies by combining actual engineering. Combining the Qingdao subway project, Yang [2] analyzed the applicable characteristics of the arch-cover method and the double-sided guide pit method along the way; Mou [3] carried out a comprehensive numerical analysis of the stress displacement, and plastic area of each construction process of the arched cover method. For the primary support arch-cover
method, Zhang [4] analyzed the variation laws of surrounding rock stress, deformation, and surface settlement during the whole excavation through model tests, field tests, and COMSOL numerical simulations. The limited overburden thickness under different conditions of surrounding rock grades were studied. In terms of the two-line arch method, Wang [5] took the Musui line as the research object and used theoretical analysis, geological analysis, field tests, and model calculations to study the initial stage of the double layer application effect of support in large deformation tunnel. In addition, for the new double-layer preliminarily supported arch cover method, Du [6] studied the double-layer preliminarily supported arch cover through theoretical derivation and numerical simulation, structural design methods, construction techniques and monitoring and measurement methods.

This paper analyzes the numerical calculation of the whole excavation process of the primary support arch-cover method, its excavation stability and applicability of the construction method, and provides a certain reference for similar projects.

2. Engineering Geology
The stratum distribution of the station area from the ground surface can be divided into artificial soil filling layer and bedrock layer. The filling layer is poor in compactness, which is mainly composed of silty clay, weathered sand with some crushed stones, low strength, poor self-stability, strong water permeability, and thickness of $1.40 \sim 4.80$ m. The bedrock is dominated by granite, and partly exposed late porphyry veins. The rock quality is typical of broken rocks. And because of tectonic compression, most of the bedrocks are distributed in the range of tectonic fracture zone, and they are divided into strong, medium and slightly weathered granite in order from shallow to deep, and the quality grades are $V \sim III$. The rock formations are undulating, the arch of the station excavation section is located in strong and moderate weathering rock formations, and the cave body is located in medium and light weathering rock formations as shown in Fig.1.

![Figure 1. Geological profile of station](image)

3. Stability analysis of primary support arch-cover method
FLAC-3D was used for numerical simulation analysis, considering the interaction of surrounding rock and structure, and the step-by-step construction process. The left and right horizontal calculation range of the calculation model is 3 times the span of the station, the vertical calculation range is taken up to the free surface, and 3 times the height of the tunnel is taken downward. The model size is $140m \times 78m$, and the tunnel depth is set to 7m. The calculation structure model is shown in Fig.2, and a total of 13,650 units were generated.
3.1. Calculation parameters
The main physical and mechanical parameters of the surrounding rock and the mechanical parameters of the supporting structure are shown in Table 1.

Table 1. Physical and mechanical parameters of surrounding rock.

| Lithology                   | Elastic modulus (GPa) | Poisson ratio | Lateral pressure coefficient | Internal friction angle (°) | Natural density (g/cm²) |
|-----------------------------|-----------------------|---------------|------------------------------|-----------------------------|-------------------------|
| Miscellaneous fill          | 0.01                  | 0.30          | 0.55                         | 10                          | 1.75                    |
| weathered granite           | 1                     | 0.24          | 0.32                         | 45                          | 2.30                    |
| Intensively weathered granite | 1                    | 0.23          | 0.30                         | 50                          | 2.30                    |
| Moderately weathered granite | 5                    | 0.22          | 0.20                         | 55                          | 2.61                    |
| Slightly weathered granite | 22                   | 0.20          | 0.15                         | 65                          | 2.63                    |

3.2. Excavation procedure
In this model, the constitutive model of the surrounding rock of the tunnel adopts the Mohr-Coulomb model to consider the non-linear deformation of the surrounding rock. The lining structure adopts beam unit, and the anchor rod adopts Bolt unit. The support of the large pipe shed and the grouting of the leading small ducts adopt plane strain units, which is equivalent to grouting reinforcement. The calculation steps are performed strictly in accordance with the tunnel excavation order as shown in Fig.3.
3.3. Simulation results analysis

(1) Stress change

As shown in Fig. 4, the vertical stress of the surrounding rock of the station arches gradually increases with the excavation of the station, and the increasing speed is first gradual, then gains momentum, and then slows down. Station arch’s response to excavation in the monitoring section is more gradual.

(2) Change in vault displacement

The figure 5 shows that the variation in the displacement of the vault. With the continued advance in excavation, the surrounding rock of the station vault experiences three stages: slow, rapid, and stable deformation stages. When the excavation surface reaches the second step, the surrounding rock begins to deform. With the continuous advancement of the face, the deformation rate is gradually accelerated. When the cross-section is monitored, the rate reaches a peak. After passing through the monitoring surface, the deformation rate gradually decreases and enters the steady deformation stage.
Figure 6. Floor heave and clearance convergence change

As shown in Fig. 6, the deformation of the station floor owing to the excavation is not obvious. The deformation of the two sidewalls is predominantly caused by the deformation of the lateral stress after excavation, and the deformation is approximately 0.038 mm, while the floor elevation is approximately 0.018 mm.

To summarize, the effect of the primary-support arch method on the excavation of the station floor and clearance is small.

In the whole simulation of excavation process, the displacement of surrounding rock changed the most at the process of removing the mid-pillar. As a result, the risk was greatest at this stage, special attention should be paid to monitoring and measuring. But in general, the settlement and displacement of the above calculation results met the design requirements, so the surrounding rock and composite support structure were all in a safe state in the construction process.

4. Conclusion
In this paper, FLAC-3D finite difference method is used to simulate the effects of stratum settlement and structural stress during the construction of the primary support arch-cover method. The analysis leads to the following conclusions:

(1) After calculation analysis and engineering practice, the construction of super shallow buried large-span tunnels using the primary support arch-cover method can meet the strength and deformation requirements. The maximum displacement of the arch is about 15mm, which meets the safety control standards for station construction.

(2) When excavating the outer lining of the rock mass in the middle of the arch, the maximum principal stress appears at the arch foot position, which is more than double the high stress area of the arch part. Therefore, the arch foot is likely to occur when the composite arch cover method is applied. Due to the large internal force, special attention should be paid to the reinforcement of the corresponding parts, such as the setting of large arch feet, the setting of reinforcement anchor cables, the setting of reinforced connection reinforcing bars and other structural measures.

(3) During the excavation of the outer lining of the rock mass in the middle of the arch, the displacement of the shallow buried soil above the arch top is distributed in an anticline layer, the maximum displacement of the soil above the arch top position, the maximum settlement of the ground
surface, and the distance from the top of the arch. The further the bit is, the smaller the change in displacement is. During the construction of the initial support of the inner layer and the neutral pillar, during the initial support of the second layer and the neutral pillar, the stress reached a maximum value, the displacement layered distribution area continued to develop, and the displacement sub-zones of each layer were approximately perpendicular to the horizontal plane. At this time, monitoring should be increased. Frequency, and timely support and other processing based on measured data.

References
[1] Jia, G.B. (2011) Application of arch cover method in construction of metro station. Journal of Cooperative Economy and Science, (12): 125-127.
[2] Yang, Z.N, Ji, Z.Q, Liu, Q.W. (2014) Model test study on stability of surrounding rock of tunnel by arch cover method. Modern Tunneling Technology, 51(05): 85-91.
[3] Mou, X.W. (2017) Stability analysis and dynamic risk assessment of arch cover method for metro station caverns. Master thesis, Shandong University, Jinan, China.
[4] Zhang, S. J. (2017) Study on mechanical effect and applicability of excavation of initial support arch cover method for rock metro station. Master thesis, Shandong University, Jinan, China.
[5] Wang, H.C. (2013) Research on application technology of double-deck initial support in large deformation tunnel. Master thesis, Southwest Jiaotong University, Chengdu, China. [In Chinese.]
[6] Du, Z.J. (2014) Analysis of ground settlement in arch cover construction of long-span tunnel. Railway Standard Design, 58(03): 110-118.