Numerical Simulation and Analysis of Advance Pre-support for Underground Cross-street Tunnel

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Abstract: In this paper, the excavation process of a cross-street tunnel construction is studied. In order to ensure the normal construction, three kinds of advanced support combination schemes are preliminarily worked out. Scheme one: leading anchor pipe + sleeve driving small pipe Grouting; Scheme two: horizontal rotary jet grouting piles+ sleeve driving small pipe grouting; scheme three: horizontal rotary jet grouting piles+ large pipe shed+ sleeve driving small pipe grouting; Combined with the existing practical engineering cases, using the finite element software ANSYS to simulate the tunnel excavation process and verify the results, the settlement and displacement curves of the surface and vault and the convergence time history curves of the side walls are compared, and the effect of structural stress control is analysed. Among them, the third scheme has great advantages. Therefore, considering all factors, the third scheme is adopted as the pre-support scheme of the tunnel.

1. Introduction

In the process of the construction of Shallow and Large Section Tunnel in Loose Stratum, the advance pre-support methods in common use are as follows: advance anchor bolt, leading small pipe, leading pipe roof, horizontal rotary grouting, etc.[1-5]. These methods can effectively control collapse, but it is easy to cause excessive ground subsidence because of their small stiffness [6]. Therefore, it is necessary to adopt the combination of two or more advanced pre-support methods, in order to control the value of surface subsidence within a reasonable range.

2. Project description

A cross-street tunnel project is to be built, which connects the two commercial underground buildings. The middle line of the tunnel is perpendicular to the middle line of the road above and crosses the Pearl River Road. The tunnel is constructed by subsurface excavation method with a length of 36.7 meters, a depth of 5 meters, a structure width of 16 meters, a height of 6.3 meters, a clear width of 14 meters and a clear height of 3.5 meters. The strata of the tunnel are mainly from top to bottom: artificial filling layer, silty clay (soft plastic), medium-coarse sand, silty clay (hard plastic), strong weathered fine sandstone, medium-weathered fine sandstone and micro-weathered fine sandstone.

Three kinds of advanced support combination schemes are preliminarily worked out to ensure the normal construction. Scheme one: leading anchor pipe + sleeve driving small pipe grouting; Scheme two: horizontal rotary jet grouting piles+ sleeve driving small pipe grouting; Scheme three: horizontal rotary jet grouting piles+ large pipe shed+ sleeve driving small pipe grouting; In order to ensure the stability of the excavating tunnel face soil and control groundwater loss, the
above-mentioned schemes are combined with deep hole grouting reinforcement measures. The finite
element software ANSYS is used to simulate and verify the results, and a reasonable pre-support
scheme is given.

3. Establishment of finite element model

3.1 Parameters setting

In the process of analysis in the paper, the elastic-plastic constitutive model and Drucker-Prager yield
criterion are adopted for both rock soil and horizontal jet grouting piles, and elastic constitutive model
is put into use for concrete structure and pre-supporting pipe sheds. According to the principle of
equivalence, it is simplified as an arch reinforcement ring with the same thickness as the effective
range of grouting, by means of increasing the cohesion and internal friction angle of surrounding rock
to simulate the effect of grouting support. The soil mechanics indexes, considering the site
construction quality, the pile test results and the numerical simulation, are shown in table 1.

| Material type                        | Unit weight (kN·m⁻³) | Modulus of elasticity (MPa) | Poisson ratio | Cohesion (kPa) | Internal friction angle (°) |
|--------------------------------------|----------------------|-----------------------------|---------------|----------------|-----------------------------|
| Miscellaneous fill                   | 16                   | 10                          | 0.35          | 6              | 10                          |
| Silty clay                           | 17.7                 | 16.5                        | 0.32          | 8              | 10                          |
| Medium sand coarse sand              | 20                   | 75                          | 0.3           | 10             | 30                          |
| Strongly weathered fine sandstone    | 22                   | 135                         | 0.25          | 20             | 40                          |
| Strongly weathered coarse sandstone  | 20                   | 188                         | 0.2           | 200            | 32                          |

By consulting a large number of relevant documents, and summarizing similar construction cases
and previous experimental results, the changes of physical and mechanical indexes of horizontal jet
grouting piles and consolidated soils in clay and sand layers are collected. The soil mechanics indexes,
considering the site construction quality, the pile test results and the numerical simulation, are shown
in table 2.
Table 2 The stratum parameters of tunnel

| Material type                          | Unit weight (kN·m⁻³) | Modulus of elasticity (MPa) | Poisson ratio | Cohesion (kPa) | Internal friction angle (°) |
|----------------------------------------|----------------------|----------------------------|---------------|----------------|-----------------------------|
| Clay Grouting Reinforcement Zone       | 18                   | 60                         | 0.29          | 70             | 32                          |
| Rotary Shotcrete Reinforcement of Clay | 23                   | 138                        | 0.24          | 200            | 35                          |
| Sand Grouting Reinforcement Zone       | 22                   | 80                         | 0.28          | 35             | 32                          |
| Sand-soil Rotary Shotcrete Reinforcement Body | 23               | 165                        | 0.24          | 200            | 35                          |

The permanent part of preliminary bracing is made up of four-limb steel grille frame, sprayed with 400 mm thick C20 concrete; the temporary support part is made up of I22a steel frame, sprayed with 300 mm thick concrete. The steel frame is connected by 22 steel bar with double layers and the circumferential spacing is 0.5 m. According to the principle of equivalence, the mechanical parameters of lining structure are obtained as shown in table 3.

Table 3 The lining structural parameters

| Material type    | Unit weight (kN·m⁻³) | Modulus of elasticity (MPa) | Poisson ratio | Cohesion (kPa) | Internal friction angle (°) |
|------------------|----------------------|----------------------------|---------------|----------------|-----------------------------|
| Preliminary bracing | 25                  | 28000                      | 0.2           | —              | —                           |
| Secondary lining  | 25                   | 32500                      | 0.2           | —              | —                           |
| Beams and columns | 26                   | 40600                      | 0.2           | —              | —                           |

3.2 Numerical simulation of construction process

According to the experience judgment of the influence range of underground cavern excavation, the calculation model size can generally be set at 3-5 times the width (or height) of the cavern excavation. A three-dimensional stratigraphic structure model is used for the simulation, which means: (i) the displacement in Z direction is constrained on the front and back of the model, (ii) the displacement in X direction is constrained on the two sides, (iii) the displacement in Y direction is constrained on the bottom. And the calculated boundary length of the model is 65 meters in the X direction, 11 meters in the Y direction and 34.5 meters in the Z direction.

The tunnel-horizontal jet grouting pile is simulated by solid element; the pipe shed structure is simulated by beam element; and the temporary support of shotcrete and profiled steel frame in each guide tunnel during tunnel excavation are simulated by shell element. The three-dimensional calculation model for the excavation process of tunnel is planned to divided into 14260 elements with 28922 nodes. The three-dimensional calculation model is shown in figure 1.

Figure 1 Three-dimensional calculation model
4. Calculation and Result Analysis

4.1 Contrast of settlement effect

In order to reduce the influence of boundary conditions of the model, the middle section (Z=-16m) is taken as the monitoring section, and the time history curves of surface subsidence, vault subsidence and lateral wall horizontal convergence are obtained as shown in the following figures 2～4.

The following can be derived from analysis of calculation results:

(1) Through the surface subsidence curve, the surface displacement can be obtained more intuitively when the tunnel excavation is completed. By comparing the three curves, it can be seen that the shapes of the surface settlement curves obtained by the three construction schemes are similar, and the maximum settlement points are basically in the same position. It shows that the three construction schemes will not change the shape of the surface settlement trough, but only have an impact on the maximum settlement values. Among the three pre-support schemes, the scheme 3 has the most obvious effect on controlling settlement.

(2) From the curves of tunnel vault settlement and side wall convergence, it can be seen that the tunnel excavation is divided into several small pilot tunnels in step construction. When the pilot tunnels are far away from the monitoring points, the influence on them is very small. Only when the construction is near the monitoring points, the displacement change is more obvious, which shows that the excavation of the diversion tunnels has a good effect on maintaining the stability of surrounding rock.

(3) Scheme 2 and scheme 3 are better than scheme 1 in restricting vault settlement and side wall convergence, especially in restricting vault settlement, which shows the necessity of the horizontal advance support. In terms of restricting horizontal convergence of side walls, there is little difference
between the two and three displacement values of the scheme, because the pipe shed is only laid in rotary jet grouting piles at the arch of the tunnel, and the same advanced support is adopted at the location of the side wall and the separation of the central guide holes. It shows that the affected area of the pipe shed is mainly in the arch of the tunnel, which mainly restricts the vertical displacement of the tunnel and surrounding rock.

4.2 Comparison of structural stress control effect

Table 4 Comparison of principal stress after Initial Supports

| Schemes  | First principal stress (MPa) | Third principal stress (MPa) |
|----------|-----------------------------|-----------------------------|
| Scheme two | 4.21                        | 6.74                        |
| Scheme three | 3.56                       | 5.49                        |

Table 5 Comparison of principal stress of secondary lining beam and column

| Schemes  | Top beam | Bottom beam | Middle column |
|----------|----------|-------------|--------------|
|          | First principal stress (MPa) | Third principal stress (MPa) | First principal stress (MPa) | Third principal stress (MPa) | First principal stress (MPa) | Third principal stress (MPa) |
|----------|----------|-------------|--------------|
| Scheme two | 3.95     | 8.84        | 2.04         | 7.02         | 0.95          | 12.9          |
| Scheme three | 3.38    | 7.54        | 1.77         | 6.03         | 0.79          | 11.0          |

The ANSYS calculation is not convergent, which shows that only grouting and advanced bolt support cannot guarantee the stability of soil around the tunnel and the tunnel deformation is too large. From table 4 and 5, it can be seen that the combination of pipe shed and horizontal jet grouting pile can play a better supporting role in advance support, reduce the load of initial support and secondary lining, and make the stress of tunnel lining structure more reasonable.

5. Conclusion

Comparing three kinds of pre-support schemes in restricting ground settlement and the surrounding rock displacement and controlling the structural stresses, the third scheme shows better support effects. Considering the particularity of the geographic location of the tunnel, the requirement for project quality is very high. Once the engineering accident occurs, it will cause great social impact and economic losses. Moreover, the construction of jet grouting piles is greatly influenced by surrounding rock conditions and man-made operation factors. In this project, the combination of horizontal jet grouting piles, large pipe shed and advanced grouting is adopted as the advanced support measures, considering various factors and requirements.

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