Study on optimization of excavation scheme for pilot tunnels of pile–beam–arch method in upper soft and lower hard stratum

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Abstract. Based on the Labor Park Metro Station Project in Dalian area located at the upper soft and lower hard composite stratum, in order to determine the reasonable excavation sequence and excavation footage of pilot tunnels of PBA method, the yield approach index (YAI) is introduced. The YAI of surrounding rock, surface settlement, stress of surrounding rock and LDP curves under different construction sequence and excavation footage of pilot tunnels are analyzed, and the optimal construction scheme of pilot tunnel is determined. The results show that the multi-cavity effect of the pilot tunnels gradually appears with the progressive excavation of pilot tunnels. After the completed excavation of six pilot tunnels, the shape of the surface settlement groove is basically in the form of groove. The peak value of the settlement groove is related to the excavation order of the pilot tunnels. The superposition effect to the surface subsidence is obviously observed from upper and lower pilot tunnels. The excavating sequence from top to bottom and from side pilot tunnel to central pilot tunnel is the best to control the surface settlement. Under this geological condition, the circular excavation footage of pilot tunnel should be selected as 1.5 m. The numerical simulation results¹ of pilot tunnels excavation are consistent with the field-measured results, verifying the feasibility of the simulation process. The scheme can provide the basis for the subsequent projects, as well as the construction of the subway station with similar geological conditions using pile-beam-arch method (PBA) method.

Keywords: Upper-soft and Lower-hard Stratum; Metro Station; Pile-beam-arch Method; Yield Approach Index; Cycling Excavation Footage

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1. Introduction
Most of the metro stations are built in the downtown area of the city [1~6]. The surrounding environment of the city is complex, which requires high deformation control in the construction process [7~15]. Minimal impact on the surrounding environment is highly desirable while ensuring the construction progress. As a new and widely employed excavation method in underground construction environment, pile-beam-arch (PBA) method exhibits effectively reduced influence on the surrounding surface and existing traffic [16~23].

Many scholars have studied the construction process of PBA method. For example, Liu et al. [24] investigated the mechanical impact of the supporting structure in the process construction of PBA method. Huang et al. [25] worked on the influence of PBA construction on the surrounding surface. Qu et al. [26] carried out the corresponding mechanical analysis on the side pile stress throughout PBA method-based construction. Luo et al. [27] discussed construction-induced surface deformation of the PBA method station of Beijing Metro Line 6, and concluded that the surface settlement was heavily affected by the construction of the pilot tunnel. Liu et al. [28] analyzed the stress and surface settlement of the supporting structure during the PBA construction.

Referring to these previous publications, the pilot tunnel construction process is easy to induce group effect in the construction process of PBA method, and the pilot tunnel excavation stage exhibits a critical influence on the surface. To discuss the impact of the excavation sequence of the pilot tunnel on the surface settlement and to select the reasonable excavation footage during the construction, this paper takes the PBA method construction of Dalian Metro Labor Park Station as an example, introduces the concept of yield approach index, analyzes the surface settlement, yield approach index (YAI), stress of surrounding rock and the distribution law of LDP curve under different construction schemes of the pilot tunnel, and determines the most favorable construction scheme, providing referencing materials for subsequent projects under similar phenomena.

2. Yield approach index
Yield approach index (YAI) is the ratio of the parameter describing the current status and the relative safest phase of a point, \( \text{YAI} \in [0,1] \). The strength criterion is Mohr-Coulomb criterion:

\[
F(\sigma) = \frac{1}{3} I_1 \sin \varphi + (\cos \theta_\sigma - 1/\sqrt{3} \sin \theta_\sigma \sin \varphi) \sqrt{J_2} - c \cos \varphi
\]  \( \text{Eq. (1)} \)

where \( I_1 \) is the 1st principal stress invariant, \( J_2 \) is the 2nd partial stress invariant, \( \varphi \) is the internal friction angle, \( \theta_\sigma \) is the stress lode angle.

On the \( \pi \) plane, the above equation can be expressed as:

\[
F(\sigma_x, \tau_x, \theta_\sigma) = \frac{1}{\sqrt{3}} \sin \varphi + 1/\sqrt{2} (\cos \theta_\sigma - 1/\sqrt{3} \sin \theta_\sigma \sin \varphi) \tau_x
\]  \( \text{Eq. (2)} \)

Where \( \tau_x = \sqrt{2J_2} \), \( \sigma_x = I_1 / \sqrt{3} \). Let:

\[
A = 1/\sqrt{3} \sin \varphi
\]

\[
B(\theta_\sigma) = 1/\sqrt{2} (\cos \theta_\sigma - 1/\sqrt{3} \sin \theta_\sigma \sin \varphi)
\]

\[
D = -c \cos \varphi
\]  \( \text{Eq. (3)} \)

Equation (3) can be summarized as:
In the state shown in Figure 1, from the triangle relationship, it can be concluded that:

\[
\frac{d}{D} = \frac{A' A}{A_C} = \frac{AC}{A_C} = \frac{\tau' \pi - \tau \pi}{\tau' \pi} = 1 - \frac{\tau \pi}{\tau' \pi}
\]  

Then the yield approach index is defined as:

\[
f(\sigma_x, \tau_x, \theta_\sigma) = 1 - \frac{\tau \pi}{\tau' \pi}
\]  

The coordinate of point C satisfies Equation (4), then:

\[
\tau' = ( - A \sigma_x - D ) / B ( \theta_\sigma )
\]  

By introducing equation (7) into equation (6), it is obtained that:

\[
f(\sigma_x, \tau_x, \theta_\sigma) = \frac{[1/3 \sin \phi + (\cos \theta_\sigma - 1/\sqrt{3} \sin \theta_\sigma \sin \phi) \sqrt{1 - c \cos \phi}]}{(1/3 \sin \phi - c \cos \phi)}
\]

Equation (8) is the expression of yield approach index under Mohr Coulomb criterion.

For the convenience of expression, let \( f'(\sigma_x, \tau_x, \theta_\sigma) = 1 - f(\sigma_x, \tau_x, \theta_\sigma) \), that is, in this paper, the yield approach degree close to 0 means that it tends to be stable, otherwise it tends to be destroyed.

3. Project overview

The Labor Park station is designed along Jiefang Road in a north-south direction, located at the junction of Jiefang Road and Ziwei street. The terrain of the site is relatively flat (Figure 2). The ground elevation within the station is 33.37~35.92 m, and the terrain is high in the South and low in the north. The starting mileage of Labor Park station is K7 + 531.659 m, the terminal mileage is K7 + 722.859 m, the length is 191.2 m, and the width of standard section is 23.3 m. The main body of the station is an island station with two underground floors. The width of the platform is 14 m, and the top plate of the station is covered with soil about 18.7~24.0 m. The station is constructed by PBA method, with 4 pilot tunnels in the upper row and 2 pilot tunnels in the lower row, a total of 6 pilot tunnels. The section structure of the initial support of the tunnel is straight wall arch, and the thickness of the initial support of the tunnel is 300 mm.
4. Different construction scheme design of PBA method

According to the actual construction situation, four kinds of cyclic footage schemes of 0.5, 1.0, 1.5 and 2.0 m are selected for the pilot tunnel to carry out three-dimensional numerical simulation.

Throughout pilot tunnel construction, different excavation sequences of pilot tunnel will cause different disturbance to the surface. Based on the excavation footage of existing pilot tunnel, there are four schemes for the construction of pilot tunnel: (1) A1-A2-B1-B2-C1-C2 (F1); (2) B1-B2-A1-A2-C1-C2 (F2); (3) C1-C2-A1-A2-B1-B2 (F3); (4) C1-C2-B1-B2-A1-A2(F4). Figure 3 indicates the location of pilot tunnel.

5. Simulation study on excavation scheme of pilot tunnel

5.1. Model establishment and parameters selection

FLAC3D software is selected to establish a three-dimensional calculation model for digital simulation of the station’s construction processes. Based on the excavation size of the station, regardless of the influence of the longitudinal length of the station, the calculation model is established with a height of 60 m, a width of 140 m, and a longitudinal length of 20 m. The calculation model is shown in Figure 4. In the process of simulation, the four sides of the model constrain its horizontal displacement, the bottom constrains its vertical displacement, and the top surface is set as free surface. Mohr-Coulomb material is used for soil and rocks, and elastic material is used for supporting structure. The advanced grouting reinforcement is realized by increasing the surrounding rock parameters of the reinforcement area. Also, Table 1 summarizes the physical and mechanical parameters of different materials, including soil and rocks.
Figure 4. Three-dimensional calculation model

Table 1. Physical and mechanical parameters

| Material                  | $\mu$ | $\gamma$/kN·m$^{-3}$ | $E$/MPa | $c$/kPa | $\phi$/° |
|---------------------------|-------|----------------------|---------|---------|----------|
| Filled soil               | 0.40  | 17.0                 | 13      | 10      | 15       |
| Silty clay                | 0.35  | 20.3                 | 42      | 47      | 17       |
| Strongly weathered slate  | 0.28  | 22.0                 | 180     | 60      | 30       |
| Moderately weathered slate| 0.23  | 27.0                 | 1200    | 170     | 38       |
| Primary Lining            | 0.20  | 23.0                 | 25000   | ——      | ——       |

5.2. Excavation footage analysis of pilot tunnel

Taking the excavation of pilot tunnel B1 as an example, the vault ($x = 58.66$, $y = 20$, $z = 39.59$) is monitored and Figure 5 shows the LDP curve of this measuring point under different excavation footages. In the simulation process of different excavation footages, the displacement of monitoring points increases abruptly when the excavation of tunnel is reaching the monitoring point. For instance, when the excavation footage is 0.5, 1 and 1.5m, the deformation trend of the measuring points is similar, with a maximum difference at only 0.11 mm. Notably, the largest vault settlement is obtained when the excavation footage is 2 m. Compared with the excavation footage of 0.5 m, the settlement increment is 1.10 mm. Therefore, when the footage of cyclic excavation is 2.0 m, the risk of face instability is the largest.
In Figure 6, the horizontal displacement of pilot tunnel B1 under different excavation footages is described. Briefly, the horizontal convergence value of pilot tunnel is different under varying excavation footages. When the excavation footage is 0.5, 1.0, 1.5 and 2.0 m, the horizontal convergence values of pilot tunnel are 1.02, 1.18, 1.36 and 2.09 mm respectively. In the practical excavations, the horizontal convergence control value of pilot tunnel excavation stage is 1.5 mm. When the excavation footage is within 1.5 m, the horizontal convergence value is within the control range. When the excavation footage is 2.0 m, the horizontal convergence value is greater than the field-monitored control value. Therefore, the pilot tunnel excavation footage in the actual projects should be constrained within 2.0 m, to eliminate its negative impacts on the stability and safety of the pilot tunnel.

Figure 5. LDP Curves of the vault

Figure 6. The horizontal displacement of pilot tunnel B1

The curve of the maximum principal stress of the vault \((x = 58.66, y = 20, z = 39.59)\) is presented in Figure 7. The maximum principal stress value of the monitoring point decreases suddenly when the
tunnel excavation is about to reach the monitoring point, and there is a trend of tensile failure, but there is no tensile stress. The maximum principal stress change rates (the ratio of the maximum change value to the initial value) under the four excavation footages are 28%, 31%, 37% and 48% respectively, that is, when the excavation footage is 2.0 m, the greater the stress release, the more obvious the excavation disturbance, and the poorer the stability of the tunnel.

**Figure 7.** Maximum principal stress distribution curve at the vault

To further describe the impact of disturbance onto relative rock caused by different excavation footages of the pilot tunnel, YAI calculation program is used to calculate the excavation process of pilot tunnel. In Figure 8, when 0.5, 1.0 and 1.5 m are selected as excavation footage, the maximum YAI of rock mass around the pilot tunnel is 0.85, 0.88 and 0.89 respectively. When the excavation footage is 2 m, the maximum YAI is 0.95. The region with YAI of 1.0 is plastic region. In the region with YAI of 0.95-1.0, the excavation of pilot tunnel is likely to cause instability and damage of surrounding rock mass, which is in the near yield state. The excavation footage is therefore determined to be 1.5 m according to the YAI evaluation results. The scheme will be adopted in the follow-up study.
5.3. Optimization analysis of excavation sequence of pilot tunnel

Four different sequences are employed to simulate and analyze the pilot tunnels excavation. Upon the completion of the pilot tunnels excavation, the settlement curve of $y = 20$ surface monitoring section caused by different excavation schemes is revealed in Figure 9. After the excavation of the six pilot tunnels, the shape of the surface settlement groove basically presents a single groove shape, but with different development processes. When the pilot tunnels on both sides of the upper layer are excavated first (A1&A2), the surface settlement trough presents a bimodal shape in the excavation stage. Notably, the unimodal shape of surface settlement trough is remained upon initial excavation of the middle pilot tunnel (B1&B2 or C1&C2). The development process demonstrates the critical and determinative impact of excavation sequence of pilot tunnels on the alteration of surface settlement trough.

Figure 10 shows the surface settlement histogram of different schemes. The largest value of the surface subsidence induced by each scheme (F1–F4) is 6.74, 7.03, 8.96 and 9.52 mm, respectively. The excavation of pilot tunnels C1 and C2 has the greatest impact on the surface. The excavation of pilot tunnels on both sides of the upper layer has the least impact on the surface settlement.

By analyzing lateral construction sequence of pilot tunnel, it is clear that excavating the pilot tunnel on both sides first can better control the surface settlement, as compared with a first excavation of the middle pilot tunnel. Additionally, the analysis of the longitudinal construction sequence of the pilot tunnel suggests it is better to limit the surface settlement to excavate the upper pilot tunnel first.

According to the simulation results of surface subsidence, when the pilot tunnel is excavated following A1-A2-B1-B2-C1-C2, that is, when the construction sequence is first up and then down, first side and then middle, the disturbance caused to the ground in the construction stage of pilot tunnel is the least.
Figure 9. Surface settlement curve of different construction sequence of pilot tunnel

Figure 10. The surface settlement histogram

Figure 11 shows the distribution of YAI of rock mass around the pilot tunnel in correspondence to different excavation sequences. The yield areas of surrounding rock mass corresponding to different excavation sequence of pilot tunnel are similar. When F1 is selected for construction, the critical yield area is the smallest. When F4 is selected for construction, the maximum value of YAI is 1, that is, the plastic zone appears around the pilot tunnel. Therefore, in the process of pilot tunnel excavation, A1-A2-B1-B2-C1-C2 is the best scheme.
6. Comparison and analysis of monitoring and simulation results

To validate the rationality of the optimized cyclic excavation footage and excavation sequence of pilot tunnel in practical engineering application, K7+561–K7+581 corresponding to the simulation range is selected as the test section, with 1.5 m as the excavation footage, and pilot tunnel is excavated via A1-A2-B1-B2-C1-C2, the vault settlement and ground surface settlement in the construction process are monitored in real time manner.

After the construction of pilot tunnel, Figure 12 depicts the curves between the measured and simulated results of vault settlement and surface settlement. As can be seen, the vault settlement rate increases rapidly when the tunnel excavation reaches the monitoring site. With an increasing distance between tunnel excavation and the monitoring point, the settlement rate gradually slows down. The settlement curve of the measured section is consistent with that of the simulated results. A single groove shape is observed from the surface settlement curve. The settlement directly above the center line of the station is the largest, and the surface settlement steadily decreases from the center line of the station to both sides.

The maximum values of the ground settlement of the field measurement results and the simulation results are 7.54 mm and 6.74 mm respectively, which are close to each other. The numerically simulated results are highly consistent with these field-measured profiles. Therefore, the PBA method assisted construction process of pilot tunnels is predictable using the developed model. The accuracy of parameters selection is verified by crosschecking the field-monitored results with the simulated results. Moreover, the model and parameters are potentially useful for simulating the excavation process of the stations in the future.
7. Conclusions

(1) The YAI can be effectively applied to the whole process of pilot tunnel excavation with PBA method, and the risk degree of rock and soil around the pilot tunnel not entering the plastic zone can be divided, which provides a reliable reference for evaluating the safety of pilot tunnel in construction process.

(2) Throughout the pilot tunnel excavations, on the premise of ensuring the construction safety, according to the evaluations of the surrounding rock deformation, stress and YAI, the excavation footage of pilot tunnel should be 1.5 m. When the 6th pilot tunnel is excavated, the shape of the surface settlement groove basically presents a single groove shape but with different development processes. The construction sequence of pilot tunnel from top to bottom and from side to middle has the best control effect on surface settlement. The superposition effect to the surface subsidence is obviously observed from upper and lower pilot tunnels.

(3) The numerically simulated results are highly consistent with these field-measured profiles, demonstrating the feasibility of the excavation scheme of pilot tunnel. The scheme can offer a referring example for the follow-up constructions of the project, and the other PBA method assisted construction of subway station under similar geological conditions.

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