Study of risk control during the departure and reception of shield in the underground shield construction in Beijing

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Abstract

The shield construction method was adopted in a subway project in Beijing, between subway stations. The departure and reception of shield machine is a key process in shield construction. To prevent major risk accidents including soil collapse at the entrance, and the displacement or deformation of shield back support, the soil around the departure and reception holes of the shield was reinforced by the jet grouting pile method. According to calculation, the shearing strength and tensile strength of the soil are significantly improved after reinforcement. The reinforced soil has good stability, which avoids the occurrence of sliding failure and reduces the probability of the occurrence of major risk accidents during the departure and reception of shield.

Keywords: shield, risk, reinforcement, stability.

1. INTRODUCTION

The departure and reception of shield machine is a very important part of shield construction(Mo et al., 2014; Yang et al., 2014; Wang et al., 2012), which directly determines the deviation of tunnel axis and the tunnel quality of the successive process. This part has a great deal of work. If the shield machine cannot precisely complete departure and reception, various risks are easy to take place. For example, during the shield machine entering the tunnel, if the pedestal deforms, the large deviation between the actual tunneling axis and designed axis will take place, which affects the normal tunneling process. During the shield machine leaving the tunnel, over-sized thrust, or nonuniform support force, will result in local deformation or displacement of back support. If the soil stability outside the sealing door is poor while no reasonable reinforcement measure is taken, soil inburst will take place in working wells after demolition. Thus, the ground surface settlement will be caused, which brings great harm to underground utilities and surrounding buildings(Zhang et al., 2016; Yan et al., 2011; Zhang and Wu, 2015; Wang et al., 2012).

2. PROJECT OVERVIEW

Line 14 of Beijing Subway is 47.3km in length and has 36 stations. It starts west from Zhangguozhuang station in Lugou bridge of Fengtai district, and terminals east to Shangezhuang station in Wangjing area. The 07-section ranges from K16+285.299 to K17+173.4. It contains one station and one metro section, as displayed in Table 1.
### Table 1 General schedule of the 07-section project of Line 14 of Beijing subway

<table>
<thead>
<tr>
<th>Civil engineering construction blocks</th>
<th>Project overview</th>
<th>Construction methods</th>
<th>Construction scale</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>07-Section</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Xitieying station</td>
<td>Open excavation</td>
<td>m²</td>
<td>15509</td>
<td>Station</td>
</tr>
<tr>
<td>Xitieying station-Youanmenwai station</td>
<td>Shield</td>
<td>mm</td>
<td>704.7</td>
<td>Single line</td>
</tr>
</tbody>
</table>

(1) Xitieying station (Open excavation)

Xitieying station locates at the south of Liangshuihe and the east of Jingkaidong road. The south side of the planning road red-line locates inside the planning green land. The layout of station main body is eastern-western.

The station is an underground three-floor island-like station and has a platform width of 12.2m, a standard section width of 21.5m and an overall length of 194.60m. The calculation platform center mileage of Xitieying station is K16+391.500, while the embedded depth of the station is 23m.

The station entrance-exits are arranged at the southeast quadrant of the intersection between Yulinan road, Liangshuihenan road, and Jingkaidong road. The No. 1 entrance-exit locates at the eastern of Jingkaidong road, close to the red-line of Yulinan road and Liangshuihenan road. The No. 2 entrance-exit is arranged at the south-eastern corner of the station and close to the red-line of Yulinan road and Liangshuihenan road. The eastern and western air channels of the station are arranged at the south of the station main body. Two sets of wind pavilions are located in the planning green land.

The station major and accessory structures are constructed by the open-excavation method. Meanwhile, the enclosure structures are constructed by the combination of cast-in-situ bored pile+steel support system and cast-in-situ bored pile+ anchor cable system. The major structure is a reinforced concrete frame structure, and an underground three-layer three-span structure.

The two terminals of the station are connected to the shield section, with launching shafts set at both terminals. A track panel shaft is set at the center of the station.

(2) Xitieying station - Youanmenwai station (shield construction)

The Xiteiying station - Youanmenwai station section locates at the southwest corner of Beijing city, between the South 2nd Ring and South 3rd Ring. It belongs to Fengtai district. Starting from Xitieying station, the section extends eastward and crosses Liangshui river in the southeast corner of Liao-Jin relics. Afterward, it exterminals right to the east, along the north bank of Liangshuihe and connects Youanmenwai station after crossing Youanmenwai street. Its single line length is 704.7m.

The section is constructed by the shield construction method. A contact channel is set at the center part, while no interval pumping station is arranged.

### 3. MEASURES TO CONTROL RISKS DURING SHIELD MACHINE DEPARTURE AND RECEPTION
The departure and reception of shield machine is a very important part of shield construction, which directly determines the deviation of tunnel axis and the tunnel quality of the successive process (Cascetta et al., 2016; Li et al., 2015). This part has a great deal of work. If the shield machine cannot precisely complete departure and reception, various risks are easy to take place. For example, during the shield machine entering the tunnel, if the pedestal deforms, the large deviation between the actual tunneling axis and designed axis will take place, which affects the normal tunneling process. During the shield machine leaving the tunnel, over-sized thrust, or nonuniform support force, will result in local deformation or displacement of back support. If the soil stability outside the sealing door is poor while no reasonable reinforcement measure is taken, soil inburst will take place in working wells after demolition. Thus, the ground surface settlement will be caused, which brings great harm to underground utilities and surrounding buildings.

According to empiric data of risk events during the departure and reception of shield machines, the occurrence probability of each kind of risk at this stage is analyzed, as listed in Table 2.

### Table 2 Probability of risk accidents

<table>
<thead>
<tr>
<th>Risk factors</th>
<th>Uncontrollability</th>
<th>Unpredictability</th>
<th>Loss</th>
<th>Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tunnel entrance soil collapse</td>
<td>0.5</td>
<td>0.56</td>
<td>0.3</td>
<td>0.5</td>
</tr>
<tr>
<td>Shield machine pedestal deformation</td>
<td>0.2</td>
<td>0.4</td>
<td>0.6</td>
<td>0.3</td>
</tr>
<tr>
<td>Deformation or displacement of back support of shield machine</td>
<td>0.1</td>
<td>0.2</td>
<td>0.5</td>
<td>0.7</td>
</tr>
<tr>
<td>Soil burst during chipping away the sealing door</td>
<td>0.1</td>
<td>0.6</td>
<td>0.8</td>
<td>0.7</td>
</tr>
<tr>
<td>Water burst during reception</td>
<td>0.5</td>
<td>0.7</td>
<td>0.3</td>
<td>0.8</td>
</tr>
<tr>
<td>Attitude mutation during departure</td>
<td>0.3</td>
<td>0.6</td>
<td>0.3</td>
<td>0.5</td>
</tr>
<tr>
<td>Axis deviation during departure</td>
<td>0.2</td>
<td>0.5</td>
<td>0.6</td>
<td>0.2</td>
</tr>
</tbody>
</table>

Hence, to avoid major risk accidents during shield machine departure and reception, it is crucial to protect the soil stability and reinforce terminal soil mass.

### 3.1 Principle, requirement, and range of reinforcement

(1) Principle of soil reinforcement.

First, based on parameters of a geological survey conducted on the project formation, the range and method of reinforcement are decided.

Second, after deciding the range and method of reinforcement, the safety during shield machine departure and reception, and sealing door demolition should be ensured.

(2) Requirement of reinforcement.

First, after soil reinforcement, both the independence and homogeneity of soil should be ensured. Besides, no obvious water seepage is allowed on the tunneling working face.
Second, two indexes should be meet: unconfined compressive strength higher than 0.8MPa; permeability coefficient lower than $1 \times 10^{-7}$ cm/s.

(3) Range of reinforcement.

The range requiring reinforcement is: before shield machining passing through the shield zone and station connector, the range with 3m wider than the tunnel in the up, down, left and right directions; the length is 8m at the launching terminal and 6m in the terminal terminal. Jet grouting piles with dimensions of $\varphi 600 \times 500$ are used for reinforcement.

3.2 Construction process of jet grouting pile

Jet grouting piles are used in the reinforcement of soil around the tunnel terminal. The construction process of these piles is as follows (Li and Ge, et al., 2015; Liu et al., 2015; Xiao and You, 2014; Li et al., 2015; Wang et al., 2016; Xia et al., 2016):

(1) Conducted site clearing before reinforcement. Manpower or mechanical approaches are used to make the site flat and level. At the same time, sewer systems should be constructed. Pile points should be marked.

(2) Conducting driller insertion. The driller is moved to the designed site, and the bottom weight of drill rod is increased. During drilling, the plumb-bob test is frequently conducted.

(3) Water jet test.

After driller insertion, low-pressure (0.5 MPa) water jet test is conducted to determine whether the nozzle and pressure are proper functioning.

(4) Drilling hole.

By moving the adjusted driller to the designed site and aligning the perpendicularity, the driller head is aligned to the pile center. After water jet test, drilling can be started. The water jet pressure is increased from 0.5 MPa to 1.0 MPa, in order to reduce friction and prevent nozzle blocking. After the drilling of the first drill rod, water jet is stopped to reduce pressure. Afterward, long drill rods are connected to continue water jet drilling, until reaching the designed pile bottom position.

(5) Slurrying.

42.5# ordinary Portland cement and clean drinking water are mixed with specified ratios. According to the selected mixture ratio, water is firstly added into the bucket, followed by cement. After mixing for 10~20 min using an agitator, the mixture flows into the mud pit through a filter screen. After the second filter screening using a slush pump, the mixture flows into the mud tank. After pressurization by a high-pressure pump, the slurry is pumped into the driller for jet grouting.

(6) Jet grouting.

After drilling to the designed elevation, the upper drill rod is screwed out. Steel bars are added to seal the water jet hole. Then, the upper drill rod is installed again, and the high-pressure cement slurry is pumped to the driller. After slurry bursts out from the hole bottom, the drill rod begins to rotate and lift, conducting jet grouting from bottom
to top. Re-jetting is required to ensure pile diameter and quality when encountering special soil.

Main technical parameters: slurry pressure greater than 20 MPa, slurry density of 1.3~1.49, rotation speed of 20 r/min, lifting speed of 0.2~0.25 m/min, a nozzle diameter of 2~3 mm, and slurry flow of 80~120 L/min.

(7) Removing driller.

After finishing the jet grouting of a pile, the driller can be removed, and the jet grouting of the next pile is started.

3.3 Check calculation of reinforced soil strength and overall stability

Mechanics analysis of soil requiring reinforcement is conducted based on elastic mechanics. The part of soil is simplified into a thin rectangle sheet (Pei et al., 2016), bearing trapezoidal-distribution lateral pressure, as displayed in Fig. 1. The trapezoid top is $q_1$, while the trapezoid bottom is $q_1+q_0$. The thickness of reinforced soil can be calculated based on the thin sheet equation and applied in strength check calculation.

![Figure 1. Force diagram of reinforced soil](image)

(1) Soil strength check calculation.

Surface load: $q_{(x,y)} = q_1 + \frac{q_0 x}{a}$

When $x=0$, $a$,

The deflection is $\omega$, $\omega=0$

$$\frac{\partial^2 \omega^2}{\partial^2 x} = 0$$

(2)

It meets the requirement of Levy solution, by setting $\omega$ as a single Fourier series,

$$\omega = \sum_{m=1}^{\infty} f_{m(y)} \sin \frac{m \pi x}{a}$$
Similarly, the load is also set as a single Fourier series:

\[ q_{(x,y)} = \sum_{m=1}^{\infty} q_{m(x,y)} \sin \frac{m\pi x}{a} \]  

(4)

\[ q_{m(x,y)} = \frac{2}{a} \int_{-a}^{a} q_{(x,y)} \sin \frac{m\pi x}{a} \, dx \]

Where,

\[ = \frac{2q_1}{\pi m} (1 - \cos m\pi) + \frac{2q_0(-1)^{m+1}}{m\pi} \]

(5)

By substituting Eqs. (1) and (2) into the basic differential equation of thin sheet deformation

\[ \frac{\partial^4 \omega}{\partial x^4} + 2 \frac{\partial^2 \omega}{\partial x^2 \partial y^2} + \frac{\partial^4 \omega}{\partial x^4} = \frac{q_{(x,y)}}{D}, \]

There is:

\[ \frac{d^4 f_m}{dy^4} - 2\left(\frac{m\pi}{a}\right)^2 \frac{d^2 f_m}{dy^2} + \left(\frac{m\pi}{a}\right)^4 f_m = \frac{q_m}{D} \]

(6)

The particular solution of Eq. (4):

\[ F_m = \frac{2q_0a^4}{D(m\pi)^3} (1 - \cos m\pi) + \frac{2q_0a^4}{D(m\pi)^3} (-1)^{m+1} \]

(7)

Where is the sheet flexural stiffness:

\[ D = \frac{Et^3}{12(1 - u^2)} \]

(8)

By substituting Eq. (5) into Eq. (1), we can get:

\[ \omega = \sum_{m=1}^{\infty} (A_m \sin \frac{m\pi y}{a} + B_m \sinh \frac{m\pi y}{a} + C_m \cos \frac{m\pi y}{a} + D_m \sin \frac{m\pi y}{a} + E_m \sinh \frac{m\pi y}{a} + F_m) \sin \frac{m\pi x}{a} \]

(9)

Since the load and boundary condition are symmetric about \( x \), \( \omega \) is also symmetric about \( x \). Hence, it can be determined that \( \omega \) is the even function of \( y \), and \( B_m = C_m = 0 \).

Equation set:

\[ \begin{cases} 
F_m + A_m \cosh \frac{m\pi y}{a} + D_m \sinh \frac{m\pi y}{a} = 0 \\
(A_m + 2D_m) \cosh \frac{m\pi y}{a} + D_m \sinh \frac{m\pi y}{a} = 0 
\end{cases} \]

(10)

After setting:

\[ \begin{cases} 
A_m = -\frac{F_m + D_m \sinh \frac{m\pi y}{a}}{\cosh \frac{m\pi y}{a}} \\
D_m = \frac{F_m}{2 \cosh \frac{m\pi y}{a}} 
\end{cases} \]

(11)

There is:

\[ \omega = \sum_{m=1}^{\infty} (A_m \sin \frac{m\pi y}{a} + D_m \frac{m\pi y}{a} \sinh \frac{m\pi y}{a} + F_m) \sin \frac{m\pi x}{a} \]

(12)
Since the load is symmetric about $x$, the maximum stress is on $y=0$. By substituting $y=0$ inside, we can get:

$$\frac{\partial^2 \omega}{\partial x^2} = \sum_{m=1}^{\infty} -\left(A_m + F_m \right) \frac{m^2 \pi^2}{a^2} \sin \frac{m \pi x}{a}$$

$$\frac{\partial^2 \omega}{\partial y^2} = \sum_{m=1}^{\infty} \left(A_m + 2D_m \right) \frac{m^2 \pi^2}{a^2} \sin \frac{m \pi x}{a}$$

$$\frac{\partial^2 \omega}{\partial x \partial y} = 0$$

Then:

$$\sigma_x = -\frac{E_z}{1-u^2} \left( \frac{\partial^2 \omega}{\partial x^2} + u \frac{\partial^2 \omega}{\partial y^2} \right)$$

$$\sigma_y = -\frac{E_z}{1-u^2} \left( \frac{\partial^2 \omega}{\partial y^2} + u \frac{\partial^2 \omega}{\partial x^2} \right)$$

$$\tau_{xy} = 0$$

Two principle stress, $\sigma_x$ and $\sigma_y$ can be obtained. According to the Mohr’s circle, the maximum bending stress and maximum shear stress of the reinforced soil are:

$$\sigma_{\text{max}} = \sigma_x \text{ or } \sigma_{\text{max}} = \sigma_y$$

$$\tau_{\text{max}} = \frac{\sigma_x - \sigma_y}{2}$$

If $\sigma_{\text{max}}$ and $\tau_{\text{max}}$ satisfying: $\sigma_{\text{max}} < (q_c)/(k_1)$, $\tau_{\text{max}} < (\tau_c)/(k_2)$, indicating that after reinforcement, the tensile strength and shearing strength of the soil are both improved and reach the standard requirement. Thus, the soil is protected from strength failure.

Where $q_c$ is the tensile strength of reinforced soil; $\tau_c$ is the shearing strength; and $k_1$ and $k_2$ are the safety factors.

(2) Check calculation of overall stability.

Sandy soil landslide often takes place at the linear slide plane (Li et al., 2012; Chen et al., 2012; Lu et al., 2016; Yao and Kong, 2012; Liu et al., 2005). The sliding models of soil before and after reinforcement are illustrated in Figs. 2 and 3:
Overall slippage analysis of soil before and after reinforcement is conducted:

Before reinforcement:

Soil downward sliding force: \[ T = (W_1 + W_2) \sin \theta \]  \hspace{1cm} (19)

Soil supporting force: \[ N = (W_1 + W_2) \cos \theta \]  \hspace{1cm} (20)

Soil sliding resistance: \[ T' = N \tan \phi = (W_1 + W_2) \cos \theta \tan \phi \] \hspace{1cm} (21)

Soil safety factor: \[ K = \frac{T'}{T} = \frac{\tan \phi}{\tan \theta} \] \hspace{1cm} (22)

After reinforcement (dashed area indicates reinforced soil):

Soil downward sliding force: \[ T = (W_{11} + W_{12} + W_{21} + W_{22}) \sin \theta \]  \hspace{1cm} (23)

Soil supporting force:
\[ N_1 = (W_{11} + W_{21}) \cos \theta \]
\[ N_2 = (W_{12} + W_{22}) \cos \theta \] \hspace{1cm} (24)

Soil sliding resistance:
\[ T_1' = N_1 \tan \phi_1 + c_l = (W_{11} + W_{21}) \cos \theta \tan \phi_1 + c_l \]
\[ T_2' = N_2 \tan \phi_2 = (W_{12} + W_{22}) \cos \theta \tan \phi_2 \] \hspace{1cm} (25)

Soil safety factor: \[ K = \frac{T_1' + T_2'}{T} \] \hspace{1cm} (26)

Where \( c \) is the soil cohesive force after reinforcement; \( l = b / \cos \phi \) and \( b \) are the thickness of reinforced soil.

(3) Check calculation examples of reinforced soil strength and overall stability.

The launching terminal of a shield tunnel in Beijing subway was reinforced by jet grouting, and elastic mechanical calculation was conducted.
The geological examination was firstly conducted on the launching terminal soil, as displayed in Table 3.

**Table 3** Geological examination results of the launching terminal

<table>
<thead>
<tr>
<th>Formation</th>
<th>Natural unit weight</th>
<th>$c$</th>
<th>$\omega$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Floury soil filling 2.5m</td>
<td>18.1</td>
<td>22</td>
<td>25</td>
</tr>
<tr>
<td>Floury soil 0.6m</td>
<td>18.5</td>
<td>22</td>
<td>26</td>
</tr>
<tr>
<td>Silty-fine sand 3.4m</td>
<td>20.6</td>
<td>0</td>
<td>30</td>
</tr>
<tr>
<td>Medium-coarse sand 4.5m</td>
<td>20.7</td>
<td>0.6</td>
<td>0.7</td>
</tr>
<tr>
<td>Rounded pebble 1.3m</td>
<td>21.0</td>
<td>0</td>
<td>40</td>
</tr>
<tr>
<td>Silty clay 2.4m</td>
<td>19.2</td>
<td>43</td>
<td>11</td>
</tr>
<tr>
<td>Medium-coarse sand 2.0m</td>
<td>21.0</td>
<td>0</td>
<td>35</td>
</tr>
<tr>
<td>Gravel 1.3m</td>
<td>21.5</td>
<td>0</td>
<td>43</td>
</tr>
</tbody>
</table>

Where $c$ stands for the cohesive force and $\omega$ is the internal frictional angle.

1. **Strength check calculation of reinforced terminal.**

Reinforced soil parameters: axial length of 6m; width of 12.6m; thickness of 10m; vault of 2m; tunnel bottom of 2m; 3m at both right and left sides; soil cohesive force $c$ is 0.07MPa; compressive strength $q_c$ is 0.8~1.0 MPa. Since the tensile strength of soil is far lower than its compressive strength, about 15%, hence, the tensile strength of reinforced soil is $q_c$ about 0.12 MPa.

Based on theoretical analysis of reinforced soil parameters, the maximum soil tensile stress occurs at the line:

$$y = 0, \quad z = -3.$$

By equally dividing the 0~a range of this line into 500 parts, the $\sigma_{max}$ and $\tau_{max}$ of each point are calculated using MATLAB. By comparing the calculation result and selecting the maximum value, $\sigma_{max}=98.4kPa$ and $\tau_{max}=14.7kPa$ at the edge of the sheet center line can be obtained. At the moment, the coordinate of $x, y, z$ is (5.91, 0, -3).

The extreme shearing strength of soil after reinforcement can be estimated as:

$$\tau_c = \sigma \tan \phi + c$$

By setting $k_1 = k_2 = 1.2$, there is: $\sigma_{max} < \frac{q_c}{k_1}, \tau_{max} < \frac{c}{k_2} < \frac{\tau_c}{k_2}$.

It is obvious that the maximum shear stress $\tau_{max}$ and tensile stress $\sigma_{max}$ after reinforcement are both lower than the shearing strength and tensile strength of the soil. Hence, it is implied that the soil strength is enhanced after reinforcement, with its stability ensured.

2. **Check calculation of stability.**

By adopting the soil mechanics equation:

$$\theta = 45^\circ + \frac{\phi}{2}$$

(28)
By calculating the soil rupture angle, there is \( \theta = 60^\circ \), thereby, the soil safety factor \( K = 2.1 \) can also be calculated. It is indicated that the soil stability is favorable after reinforcement and sliding failure is successfully prevented.

4. CONCLUSIONS

The departure and reception of shield machine is a key part of shield construction. If the departure and reception can not be precisely completed, various risk problems are possible to take place, such as soil collapse, pedestal deformation, local deformation or displacement of shield back support. All these risk events not only affect construction quality but also lead to serious safety accidents. To reduce the probability of these risk events, a jet grouting method was applied in this study to reinforce tunnel soil. After reinforcement, the shearing strength and tensile strength of soil are significantly improved. The soil possesses favorable stability, with the probability of above risk events reduced. Thus, the project quality and construction safety are guaranteed.

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6. REFERENCES


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