Study on construction risk and control technology of subway tunnel in soft soil stratum

Heng Kong, Fei Guo, Mi Zhang*, Shenglei Gao, Kaili Wang
Beijing Municipal Construction Co., Ltd., Beijing 100089
*ab20160013@xs.ustb.edu.cn
Corresponding author: Fei Guo, 2295459715@qq.com

Abstract. Taking the shield crossing Huangma road of Beijing new airport line as the engineering background, main construction risks of large section shield crossing Huangma road in soft soil layer were analyzed. Taking the support pressure of excavation face as the research object, the influence of shield excavation on the surrounding soil and surface deformation of the working face were studied, and the corresponding reinforcement measures were proposed. According to the field monitoring data after reinforcement, the settlement trough of 8.8m shield was predicted based on peck formula. The results show that the width coefficient of settlement slot of 8.8 m shield machine varies from 0.41 to 0.46, with an average value of 0.42.

1. Introduction
As an important transportation mode in modern cities, underground rail transit has the characteristics of large traffic volume, safety, speed and comfort. At the same time, it can effectively reduce pollution emissions and improve air quality. It is precisely because of these characteristics that it has been developed rapidly in urban construction. There are more than 20 cities planning, preparing for and having built rail transit in China, the total mileage of urban rail transit network has reached 3500 km.

Taking Beijing rail transit construction as an example, and at least one rail transit line every year in the future will be built. In order to implement the planning objectives, Beijing rail transit construction has entered a stage of rapid and leapfrog development. In the future, Beijing rail transit lines under construction will form a network pattern of "three rings, four horizontal lines, five vertical lines and seven radiation lines". Such a huge construction scale and investment is unprecedented in the history of rail transit construction at home and abroad.

2. Project overview
The grade of the subway crossing Huangma road is grade I, which is the main east-west passage in the south of Daxing new city. The tunnel passes through silty clay layer and silty soil layer, with multi-layer groundwater distributed. The lithology of aquifer is mainly silt and sand. The crossing length is about 60 m, the angle is about 90 ° and the distance between the tunnel top and the Huangma road surface is about 18.253 mm. The Shield Crossing under Huangma road is a secondary environmental risk source.
3. Project overview

According to the actual construction situation of Beijing metro new airport line 04 section crossing Huangma Road, the tunnel excavation area is 60.79 m², and the tunnel vault buried depth is 18.25 m. The FLAC³D calculation model is established in the area of 60 m × 36 m × 90 m (width × height × length). The model is divided into 184800 units and 192623 nodes. The 3D calculation model is shown in Figure 1.

![Fig.1. Calculation model](image)

According to the investigation report of the project, the main physical and mechanical parameters of the model are determined, and the stratum near the road is simplified as horizontal layer[2-5]. The calculation parameters of geotechnical mechanics are shown in Table 1.

| Stratum                  | Density /cm³ | Compression modulus /MPa | Poisson's ratio | Cohesion /KPa | Internal friction angle /° | Layer thickness /m |
|--------------------------|--------------|--------------------------|-----------------|---------------|---------------------------|-------------------|
| Silty sand fine sand     | 1.90         | 15.0                     | 0.25            | 0             | 20.0                      | 2.0               |
| Silt                     | 1.99         | 8.3                      | 0.25            | 21            | 22.9                      | 6.0               |
| Fine sand silt           | 2.03         | 27.5                     | 0.25            | 0             | 28.0                      | 6.0               |
| Pebble round gravel      | 2.15         | 53.0                     | 0.20            | 0             | 35.0                      | 2.0               |
| Silty clay               | 1.96         | 12.8                     | 0.29            | 36            | 13.2                      | 12.0              |
| Fine sand medium sand    | 1.99         | 20.3                     | 0.22            | 22            | 24.2                      | 8.0               |

4. Project overview

4.1. Influence of support pressure on soil around excavation face

In the process of shield construction, the original state of soil is destroyed by excavation and disturbance, which leads to stress increment of soil element and displacement of surrounding strata[6]. In the actual process of shield tunneling, the soil layer through which the shield passes is silty clay layer. In the construction of earth pressure shield tunnel, the surface heave caused by excessive support pressure will cause obvious harm to the project. Therefore, this section mainly focuses on the influence of small support pressure on the surrounding soil. The concept of support stress ratio is introduced to express the stress of excavation face [1]:

\[
\lambda = \frac{\sigma}{\sigma_0}
\]

(1)

\(\sigma\) is the support stress at the centre of the excavation face, and \(\sigma_0\) is the static earth pressure of the original stratum in the centre of the tunnel.
The soil displacement near the excavation face under different support pressures is shown in Fig. 2. It can be seen that the relationship between the soil deformation in front of the excavation face of silty clay layer and the support pressure is shown in three stages. In the first stage, the support stress of excavation face meets the requirements of limit support stress (support stress ratio is 1-0.3), and deformation is not sensitive to the decrease of support stress; In the second stage, the support stress of excavation face is close to the limit support stress (support stress ratio is 0.3-0.05), which shows that deformation is very sensitive to support stress; In the third stage, the support stress of the excavation face exceeds the critical value of the limit support stress (the support stress ratio is less than 0.05), which is the stage of support pressure failure. When the support stress ratio of excavation face is above 0.3, the maximum displacement of soil in front of the excavation face is 6.38 cm, and the maximum displacement is basically unchanged; When the support stress ratio of excavation face reaches 0.05, the maximum displacement of soil in front of excavation face is 10 cm; When the support stress ratio of excavation face is less than 0.05, the maximum displacement of soil in front of excavation face is 10.7 cm.

With the decrease of support pressure, the displacement of soil in front of excavation face increases. The horizontal displacement in the direction of the pressure chamber is significantly larger than that in the vertical direction, and the displacement mode of the soil is "bulging out".

4.2. Influence of support pressure on surface deformation
In order to compare with the simulation results, the settlement monitoring points are arranged on the longitudinal surface in front of the excavation face, and the specific settlement monitoring points are shown in Fig. 3.

When the support stress ratio is 0.05, the longitudinal surface settlement curves in front of and behind the excavation face are shown in Fig. 4. According to the calculation, the surface settlement caused by the support pressure presents a normal curve distribution similar to the cross-section settlement trough type, and the maximum settlement is about 2m in front of the excavation face. The relationship curve between support stress ratio and partial longitudinal surface settlement is shown in Fig. 5, which shows parabola relationship. The variation of surface settlement with the support pressure is similar to that of the soil in front of the excavation face, which also shows three stages.
5. Construction safety measures
According to the covering depth and geological conditions of the shield tunnel at the crossing site of
the project, combined with the actual construction experience, the earth pressure value should be
stably controlled between 0.7 and 1 bar. The actual volume of excavated single ring of shield machine
is 102.64 m³, and that of single ring is 112.9 m³. When the shield is excavated, the excavation quantity
shall be strictly controlled, so that the excavation amount of each ring is within the control range, and
it is forbidden to make more excavation. The driving speed should be controlled at 90-100 mm / min
to ensure that the shield can pass through the tunnel at a relatively uniform speed and that the
cutterhead can fully cut the soil. In the shield crossing section, the synchronous grouting material
is cement + modified sodium silicate double slurry, and the slurry setting time is controlled within 15 ~
25 s, so as to minimize the settlement and slurry loss caused by the slurry setting time. In the crossing
section, in order to ensure good sealing of shield tail and synchronous grouting effect, the amount of
sealing grease added at shield tail is increased by 2 times to ensure no water leakage and slurry
leakage.

6. Prediction of surface subsidence based on peck formula
Empirical formula method is based on a large number of measured data of surface subsidence. The
formula obtained by regression analysis has certain statistical significance and can reflect the objective
law of surface movement in this area to a certain extent. According to the monitoring data of the actual
construction process, this section proposes a k parameter range through calculation, so as to modify
the application range of peck formula in similar strata.

The prediction model of stratum settlement displacement by peck empirical formula method is as
follows:

$$S(x) = S_0 \exp\left(-\frac{x^2}{2\lambda^2}\right)$$

(2)
\[
S_{\text{ext}} = -\frac{V}{i\sqrt{2\pi}}
\]  

(3)

Among them, \( s(x) \) - the distance from the tunnel center line is the surface settlement value at \( x \) (m); \( S_{\text{max}} \) is the maximum surface settlement value at the tunnel center line (m); \( i \) is the distance from the inflection point of the surface settlement groove curve to the axis of the excavation body (m); \( V_i \) is the ground loss per unit length of the tunnel caused by construction.

According to formula (2) and (3), a reasonable range of \( K \) reference value is calculated based on the measured settlement data obtained in the actual construction process of Huangma road shield. The calculation results are shown in Table 2.

| Monitoring section | \( s \) (m) | \( S_{\text{max}} \) (m²) | \( i \) (m) | \( K \) |
|-------------------|----------|----------------|--------|-------|
| Section 1         | -0.0087  | 0.1777         | 19.9   | 7.96  | 0.40  |
| Section 2         | -0.0085  | 0.1831         | 19.9   | 8.35  | 0.42  |
| Section 3         | -0.0071  | 0.1591         | 20.1   | 8.34  | 0.41  |
| Section 4         | -0.0069  | 0.1465         | 19.9   | 8.48  | 0.43  |
| Section 5         | -0.0068  | 0.1558         | 19.9   | 8.76  | 0.45  |

It can be seen from Table 2 that the approximate variation range of \( K \) value is 0.40-0.45. In order to further accurately determine the range of \( K \) value, the method of analysis of variance is used to calculate. The variance formula is as follows:

\[
D(x) = S_{\text{ext}} \exp\left(-\frac{X_i^2}{2i^2}\right)D
\]  

(4)

Where \( d(X_i) \) is the variance; \( X_i \) is the sample; \( E(x) \) is the average value of the sample; \( n \) is the total number of samples.

According to formula 4, \( D(X_i) = 0.00025 \). The smaller the variance is, the smaller the sample difference is, and the closer to a certain determined value \( E(x) = 0.42 \). Therefore, the range of \( K \) value is 0.41-0.44. Take \( K \) values of 0.42 and 0.43 to discuss the land subsidence, and verify whether the value of \( K \) is correct, as shown in Figure 6.

The predicted maximum settlement is 6 mm by theoretical calculation and 5.78 mm by actual monitoring. There is little difference between the calculated results and the measured results, indicating that the \( K \) value in the prediction calculation is reasonable.

![Figure 6](image-url)
7. Conclusion

(1) With the decrease of support pressure of Huangma road excavation face, the displacement of soil in front of the excavation face increases continuously. The displacement of soil pressure chamber in horizontal direction is significantly greater than that in vertical direction, and the soil displacement mode is "bulge type";

(2) The surface settlement caused by support pressure presents a normal curve distribution similar to the cross-section settlement trough type, and the maximum settlement is about 2 m in front of the excavation face.

(3) In order to ensure the shield passing through the Huangma road smoothly, the earth pressure value is set between 0.7 and 1 bar to ensure the stability of earth pressure at the heading face and ensure the shield passing through at a relatively uniform speed. At the same time, reinforcement of surrounding rock mass and grouting method are proposed to ensure construction safety.

(4) In the actual construction process, a series of monitoring points are set up on Huangma Road, and the surface settlement is predicted based on peck formula. The approximate variation range of K value is 0.41-0.46, and the average value is 0.42.

Reference

[1] Zhang Z.G., Zhang M.X. Deformation prediction of subway tunnel induced by EPB shield in soft clay during above and down overlapped traversing process and its construction control [J]. Chinese Journal of Rock Mechanic and Engineering, 2013, 32(S2): 3428-3439.

[2] Bai X.F., Wang M.S. A two-stage method for analyzing the effects of twin tunnel excavation on adjacent tunnels [J]. China Civil Engineering Journal, 2016, 49(10): 123-128.

[3] Zhang Q.F., Xia T.D., Ding Z., et al. Effect of nearby undercrossing tunneling on the deformation of existing metro tunnel and construction control [J]. Rock and Soil Mechanics, 2016, 37(12): 3561-3568.

[4] Deng X.F., Chen S.G., Zhang H. A study on tunnel surrounding rock deformation control technologies of Shenzhen Subway Line No.4 [J]. Chinese Journal of Underground Space and Engineering, 2011, 7(2): 340-345.

[5] Chen H.F., Yuan D.J., Wang F. et al. Study on safe control of metro shield underpassing highspeed railway in weak stratum[J]. China Civil Engineering Journal, 2015, 48 (Suppl. 1) :256-260.

[6] Zhang C.P., Zhang D.L., Wang M.S., et al. Catastrophe mechanism and control technology of ground collapse induced by urban tunneling [J]. Rock and Soil Mechanics, 2010, 31(S1): 303–309.