Research on the Optimal Clearance Distance of Super-Large-Diameter Shield Tunnel Underpassing the Existing Metro Tunnel

Liu Nian

Shanghai Municipal Engineering Design Institute (Group) Co., Ltd, Shanghai, 200092, China

Corresponding author’s e-mail: liunian@smedi.com

Abstract. With the accelerating urbanization in China and the constant development of underground space, shield tunnels have been extensively applied to underground roads in central urban areas. However, the central areas are featured with complex surroundings, such as numerous subways, bridge pile foundations, basements, pipelines, and other structures and buildings. Therefore, it will be an unavoidable engineering difficulty for the construction of shield tunnel in the central urban area to cross at a close range buildings (structures) such as existing tunnels, underground pipelines, underground passages and basements. At present, there are remarkable research results for the crossing of subway shield tunnel with an outside diameter of 6.0 m, and rich research results for the crossing of shield tunnel with an outside diameter of 10-14 m. However, there are relatively few studies on the shield tunnel with an outer diameter of 15 m and above crossing existing buildings (structures). Based on Shanghai Beiheng super-large-diameter shield tunnel (outside diameter 15.0 m), the Midas GTS finite element analysis software was used herein to study the relation between the underpassing clearance distance $h$ and the peak settlement of existing metro tunnel $S$. The optimal clearance distance of the super-large-diameter shield tunnel underpassing the existing metro tunnel in the soft soil area $h$ was drawn to be 7.0~8.0 m. Through analysis, it was found that the ground loss rate $\rho$ and the tunnel peak settlement $S$ of the existing tunnel was linear, with the slope $= 2.795 > 1$. It proved that the tunnel peak settlement $S$ of the existing tunnel was significantly influenced by the ground loss rate $\rho$. Therefore, it’s quite reasonable to take the ground loss rate $\rho$ as the evaluation indicator and control requirement for crossing construction.

1. Introduction

With the accelerating urbanization in China and the constant development of underground space, shield tunnels have been extensively applied to underground roads in central urban areas. However, the central areas are featured with complex surroundings, such as numerous subways, bridge pile foundations, basements, pipelines, and other structures and buildings. Therefore, it will be an unavoidable engineering difficulty for the construction of shield tunnel in the central urban area to cross at a close range buildings (structures) such as existing tunnels, underground pipelines, underground passages and basements. More and more attentions are paid to studies on contents such as settlement rule, ground loss, crossing influence analysis and deformation monitoring associated with the shield tunnel construction. For example, Wang studied the settlement rule of Shanghai subway articulated shield tunnel crossing the existing buildings such as Nanbei overpassing pile foundation and school [1]; Shi et al. studied the settlement rule of Shanghai Dalian Road Yuejiang...
tunnel mud-water balance shield with an outside diameter of 11.22 m underpassing the pier pile foundation of the Huangpu River (with the vertical clearance distance 0.46 m) [2]; Huang et al. studied the construction protection technology of the Shanghai Bund soil pressure balance shield with an outside diameter of 14.27 m laterally traversing the Bund historical buildings [3]; Ge et al. analyzed the settlement rule of shield crossing the protected buildings by Z-Soil software modeling [4]; Liu et al. studied the basic mechanical properties of glass fiber reinforcement and its application in shield crossing [5]; Kong et al. studied the construction technology of small-radius shield (minimum curve radius 350m) crossing buildings [6]; Guo studied the surface deformation rule caused by large-diameter soil pressure balance shield based on measured data from Beijing Metro Line 14 [7]; Zhu analyzed the settlement rule of Tibet South Road Yuejiang tunnel crossing at a close range M8 line and causes for the subway outage based on measured data [8]; Tang and Jiang respectively studied the settlement rule of Beiheng mud-water balance shield with an outside diameter of 15.56 m underpassing line 7 and line 11 of existing metro tunnel [9-10]. At present, there are remarkable research results for the crossing of subway shield tunnel with an outside diameter of 6.0 m, and rich research results for the crossing of shield tunnel with an outside diameter of 10-14 m. In particular, the analysis of causes for the subway outage for Tibet South Road Yuejiang tunnel crossing at a close range M8 line has very engineering value. However, there are relatively few studies on the shield tunnel with an outer diameter of 15 m and above crossing existing buildings (structures). Relevant studies mainly focused on the summary of Beiheng tunnel crossing construction.

Therefore, based on Shanghai Beiheng super-large-diameter shield tunnel (outside diameter 15.0 m), the Midas_GTS finite element analysis software was used herein to analyze the optimal clearance distance of super-large-diameter shield tunnel underpassing the existing metro tunnel in the soft soil area and relation between peak settlement and ground loss rate and provide technical support for the line selection and design of shield tunnel in the central urban area.

2. Project profile

2.1. Overview

The Shanghai Beiheng shield tunnel is currently China’s largest underground road project in the central urban area. It starts from Beihong Road in the west and ends at Neijiang Road in the east. This 19.1-km road runs through the central urban area of Shanghai (6 districts of Putuo, Changning, Jing’an, Huangpu, Hongkou, and Yangpu). It includes several laying forms such as underground tunnels, overpasses and surface roads. The overall length is large and the environment along the line is
complex. The Beiheng shield tunnel has an outside diameter of 15.0 m, a lining thickness of 0.65 m, and a ring width of 2.0 m. It adopts a single-layer lining structure, as shown in Figure 1. The project uses the tunnel shield with an outside diameter of 15.56 m to start from the Zhongjiang Road shield work shaft eastward, pass through the Zhongshan Park shield work shaft with a small curve radius of $R=500$, move westward and end at the Shaiwang Factory shield work shaft, with a total length of 6.498 km, as shown in Figure 3–4. [11]

![Figure 3. Floor plan of Shanghai Beiheng shield tunnel (Zhongjiang Road shield work shaft to Zhongshan Park shield work shaft)](image)

With its super large fracture, long line and complex surrounding environment, the Beiheng shield tunnel faces many critical technical difficulties:

1. China’s first super-large-diameter mud-water balance shield passing the existing metro line 3, 7 and 11. The metro line 3 represents the down suspension arc bridge. The metro lines 7 and 11 represent the double-tube shield tunnel with an outside diameter of 6.2 m;
2. The super-large-diameter shield continuously cross over 200 buildings along the line.
3. The super-large-diameter shield works in a sharp curve, $R_{\text{min}}/D=33.3$, the smallest in China ($R_{\text{min}}$-minimal radius of plane curve, $D$-shield tunnel outside diameter);
4. The first time in China to build the internal structure of the super-long shield tunnel by the fair-faced concrete.

2.2. Crossing metro line

As shown in Figure 3–4, Beiheng shield tunnel crosses 2 times with the planning metro line and 3 times with the existing metro line. Specifically, Beiheng shield tunnel under passes the existing metro line 7, 11 and 3; the planning metro 14, 15 over pass Beiheng shield tunnel. The inground such as the correlation and minimum vertical clearance distance is detailed in Table 1.

Based on the Beiheng shield tunnel underpassing the existing metro line 11, the author will study the optimal clearance distance of Beiheng shield tunnel underpassing and relation between peak settlement and ground loss rate.
2.3. Underpassing metro line 11
The Beiheng shield tunnel will underpass at a close range the existing metro line 11 (Later referred to as M11), and its BIM is shown in Figure 2. M11 is a double-tube shield tunnel with an outside diameter of 6.2 m, a thickness of 0.35 m, an annular width of 1.2 m, and a double-line plane clearance distance of ~6.0 m. The plane projection angle between the center line of the Beiheng shield tunnel and the M11 shield tunnel is ~68°, and the overlapping length is 19.9 m, as shown in Figure 5. It is ~38m away from the center of the Beiheng shield tunnel. There is a north-south Beiheng ramp shield tunnel with an outside diameter of 7.2 m and a thickness of 0.5m. There is a sewage pipe with an outside diameter of 2.4 m above the down tunnel of M11. The Beiheng ramp shield tunnel is still under planning. Its outsider diameter, thickness and line position are not determined yet.

Table 1. List of Shanghai Beiheng shield tunnel crossing metro

| S/N | Metro line       | Passing information                  | Metro tunnel elevation(m) | Minimum clearance (m) |
|-----|------------------|-------------------------------------|---------------------------|------------------------|
| 1   | Existing metro line 7 | Beiheng shield tunnel underpassing existing metro tunnel | Tunnel bottom elevation-19.8 | 6.21                   |
| 2   | Existing metro line 11 | Beiheng shield tunnel underpassing existing metro tunnel | Tunnel bottom elevation-24.5 | 7.06                   |
| 3   | Planning metro line 14 | Planning metro tunnel overpassing Beiheng shield tunnel | Tunnel bottom elevation-13.4 | 8.22                   |
| 4   | Planning metro line 15 | Planning metro tunnel overpassing Beiheng shield tunnel | Tunnel bottom elevation-20.00 | 5.00                   |
| 5   | Existing metro line 3 | Beiheng shield tunnel crossing between the pile foundation | Tunnel bottom elevation-66.03 | Horizontal distance to pile foundation 19.3 |

The relative position relation between the section of Beiheng shield tunnel and M11 shield tunnel is shown in Figure 6. M11 up tunnel in the underpassing is covered by ~20.27 m, and the down tunnel in the underpassing is covered by ~20.52 m. The fracture soil layer of the up tunnel and down tunnel belongs to ⑤-layer gray powder clay. Beiheng shield tunnel in the underpassing is covered by ~27.62m top soil. The soil in the shield cutting area is mainly ⑦-layer floral yellow ~ gray powder sand, ⑧-layer floral yellow ~ gray fine powder sand and ⑧-layer gray clay. Beiheng ramp shield tunnel has a ~9.82 m top soil, and the vertical clearance distance with M11 shield tunnel is ~ 3.5m. The sewage pipe has ~3.93 m top soil and is located in ③-layer silt powder soil.

Figure 5. Plane position relation of Shanghai Beiheng shield tunnel underpassing M11
Figure 6. Vertical position relation of Shanghai Beiheng shield tunnel underpassing M11
Table 2. Thick of Soil layer in between of Shanghai Beiheng shield and M11 tunnel

| M11 tunnel | Vertical clearance distance(m) | Thick of Soil layer in between(m) |
|------------|--------------------------------|----------------------------------|
| M11 up tunnel | 7.48            | ⑤-1-powder clay 1.39⑥-powder clay 2.24⑦-1-powder sand 3.85 |
| M11 down tunnel | 7.06            | ⑤-1-powder clay 1.17⑥-powder clay 2.31⑦-1-powder sand 3.58 |

The soil layer between Beiheng shield tunnel and M11 shield tunnel is ⑤-layer gray powder clay, ⑥-layer dark green powder clay, ⑦-layer floral yellow ~ gray powder sand, as shown in Table 2.

3. Numerical analysis of the shield tunnel underpassing metro tunnel

3.1. Calculation model

Midas_GTS finite element analysis software is used to analyze Beiheng shield tunnel underpassing and M11 shield tunnel. The finite element model size is 150×108×65.5m, as shown in Figure 7. According to the model, the horizontal angle of Beiheng shield tunnel underpassing and M11 shield tunnel is 68°. Beiheng shield tunnel underpasses M11 tunnel at a slope of 1.47%; M11 up tunnel has a slope of 1.57%; M11 down tunnel has a slope of 1.28%.

![Figure 7. Numerical calculation model](image)

The shield support pressure is simulated by the homogeneous load. The maintenance pressure is the static soil pressure at shield centerline. The model soil layer is divided into 9 layers. Mohr-Coulomb model is used. Its physical properties are shown in Table 3. The pipe lining is an overall structure by connecting the pipe by bolts and macroscopically different in different directions. When the homogeneous equivalent pipe lining is adopted, it’s required to multiply the rigidity reduction coefficient of 0.8.

Table 3. Soil layer division and parameter value

| S/N | Layer sequence | Soil layer          | Thickness(m) | E(kPa)          | γ(kN/m3) | c(kPa) | φ(°)   |
|-----|----------------|---------------------|--------------|----------------|----------|--------|--------|
| 1   | ①             | Filling soil, powder clay | 3.2          | 37000          | 18.5     | 10     | 28.5   |
| 2   | ②             | Silt powder clay    | 8.04         | 56300          | 18.2     | 3      | 31.5   |
| 3   | ③             | Silt clay           | 5.5          | 13700          | 17.1     | 13     | 16.0   |
| 4   | ④             | Clay                | 5.8          | 13300          | 16.9     | 12     | 15.4   |
| 5   | ⑤             | Powder clay         | 7.8          | 16450          | 17.6     | 17     | 17.2   |
| 6   | ⑥             | Powder clay         | 3.83         | 37250          | 19.4     | 43     | 20.4   |
| 7   | ⑦             | Sand powder clay    | 4.88         | 73700          | 18.6     | 3      | 31.5   |
| 8   | ⑧             | Powder clay         | 7.45         | 73700          | 18.6     | 1      | 33.5   |
| 9   | ⑨             | Powder clay with sand | 12.34      | 26500          | 18.1     | 20     | 20.1   |
3.2. Calculate work condition
In the construction of the Beiheng shield tunnel, such factors as the clearance of the shield tail, the shield posture control and the soil pressure will cause deformation of the surrounding soil and thus affect M11 shield tunnel. The mainstream simulation method at present is to reflect the influence of the above factors by a single or several parameters. For example, the stress release coefficient method (or ground loss rate method) is to simulate the influence of the above factors by the stress release coefficient method (or ground loss rate method). Besides, when applying the “equivalent circle zone method”, we mainly consider the influence of the shield tail clearance and the simultaneous grouting level while ignore the influence of other factors.

Therefore, the numerical simulation of the shield crossing construction relies on the judgment of the main factors and the inversion analysis of the measured data, as well as the numerical and indexed assumptions of a number of complex factors such as the shield posture, over excavation and synchronous grouting. Therefore, the ground loss rate is used herein to evaluate the influence level of the above factors.

The model applies mandatory pipe displacement and simulates ground loss. The mandatory displacement is usually loaded by (a) uniform ring and (b) crescent gradient, as shown in Figure 8. Generally speaking, (a) when a uniform ring is used in the simulation of a small shield tunnel, the simulation results are consistent with the measured results; (b) when the crescent gradient is used in the simulation of a large and super large shield tunnel, the simulation results are consistent with the measured results. This model adopts (b) the crescent gradient simulation method. [12-13]

Numeric calculation conditions based on assumptions above:
(1) Assume the ground loss rate of Beiheng shield tunnel underpassing M11 shield tunnel is 0.5%, the relation between the clearance distance \( h \) of Beiheng shield tunnel and M11 shield tunnel and the peak settlement \( S \) of M11 shield tunnel will be analyzed to draw a relatively optimal underpassing clearance distance.

(2) Assume the clearance distance of Beiheng shield tunnel and M11 shield tunnel is 8.0 m, the relation between the ground loss rate \( \rho \) of Beiheng shield tunnel underpassing M11 shield tunnel and the peak settlement \( S \) of M11 shield tunnel will be analyzed.

3.3. Calculation results
For brevity, this paper only includes the calculation result of the ground loss rate = 0.50% and the underpass clearance distance = 7.5 m, as shown in Figure 9-10. The ground settlement of Beiheng shield tunnel underpassing M11 shield tunnel is ~12.8~20.1 mm; the up tunnel settlement of M11 shield tunnel is -15.3 mm, and the down tunnel settlement is -15.4 mm.

Figure 9. Overall subsidence cloud map
Figure 10. Settlement of M11 shield tunnel

4. Value Simulation Result Analysis

4.1. Underpass clearance distance-peak settlement relation
Based on the above calculation results, prepare the underpass clearance distance-peak settlement relevant curve (ground loss rate: 0.5%) by using the underpass clearance distance (up and down tunnel clearance distance) as X axis and the peak settlement of M11 tunnel shield as Y axis, as shown in Figure 11.

![Figure 11. Correlative curve of underpass clearance distance to peak settlement](image)

![Figure 12. Correlation curve between ground loss rate and peak settlement](image)

Use regression analysis and fit data by logarithmic formula. The fitting formula:

\[ S = -8.087 \ln(h) + 31.716 \quad (1) \]

Where: \( S \) – peak settlement of existing shield tunnel; \( h \) - up and down tunnel clearance distance.

According to regression statistics \( R^2 (R \text{ Square}) = 0.9962 \approx 1 \), the peak settlement \( S \) of existing metro tunnel and underpass clearance distance \( h \) are strongly relevant. F inspection: \( F(\text{Significance F}) = 5.97 \times 10^{-11} < 0.05 \), T inspection: \( t(\text{P-value}) = 2.93 \times 10^{-13} < 0.05 \), the regression formula shows a significant logarithmic linear relation.

According to the above fitting function, when the underpass clearance distance \( h \) is 4.3~14.7 m, the peak settlement \( S \) of existing metro is 20~10 mm;

Infer from formula (1)

\[ S' = -\frac{8.087}{h} \quad (2) \]

According to formula (2), in case of underpass clearance distance \( h < 8.0 \) m, the variation of peak settlement of existing metro is <-1.0, namely when the underpass clearance distance \( h \) is <8.0 m, the peak settlement \( S \) of the existing metro shows significant response to the variation of underpass clearance distance \( h \). Therefore, it’s more proper for the underpass clearance distance \( h \) set at 4.3~8.0 m. Besides, in consideration of the existing metro safety, it’s more proper for the peak settlement \( S \) set at 15 mm. Therefore, the optimal underpass clearance distance \( h \) is 7.0~8.0 m.

4.2. Ground loss rate distance-peak settlement relation

Based on the above calculation results, prepare relevant curve of ground loss rate \( \rho \) - peak settlement \( S \) by using the ground loss rate \( \rho \) as X axis and the peak settlement \( S \) of M11 tunnel shield as Y axis, as shown in Figure 12.

Use regression analysis and fit data by linear formula. The fitting formula:

\[ S = 2.795\rho + 5.2464 \quad (3) \]

Where: \( S \) – peak settlement of existing shield tunnel; \( \rho \) - ground loss rate of Beiheng shield tunnel underpassing.

According to regression statistics \( R^2 (R \text{ Square}) = 0.9980 \approx 1 \), the peak settlement \( S \) of existing metro tunnel and ground loss rate \( \rho \) are strongly relevant. F inspection: \( F(\text{Significance F}) = 2.694 \times 10^{-11} \).
9<0.05, T inspection: t(P-value) = 9.88×10^{-7}<0.05, indicating that the regression formula shows a significant coefficient linear relation.

The slope in formula \( (3) = 2.795 > 1 \) proved that the tunnel peak settlement \( S \) of the existing tunnel was significantly influenced by the ground loss rate \( \rho \). Therefore, it’s quite reasonable to take the ground loss rate \( \rho \) as the evaluation indicator and control requirement for underpassing construction.

5. Measured Data

The measured settlement data of Beiheng shield tunnel underpassing M11 shield tunnel are shown in Figures 13 and 14. Since the tunnel enters the influence scope of line 11, the up line relatively close to the underpassing area shows a settlement trend with the maximum settlement -0.38 mm. As the shield moves to right below the tunnel, line 11 tunnel begins to rise. As the shield continues to move forward, the maximum rise of up line 11 is 9.6 mm. When the shield moves gradually far from the up line, the up line begins to settle, with the settlement up to 3.02 mm. The down line shows the similar trend with the up line trend. The maximum rise of the down line as the shield moves is up to 12.58 mm. As the shield moves away, the tunnel begins to settle gradually, with the maximum settlement 2.2 mm.

According to measured data, in case of underpass clearance distance \( h = 7.06 \pm 7.48 \) m, the peak sediment of M11 shield tunnel is 12.58 mm, quite close to the peak settlement \( S = 15.4 \) mm from formula (1). The reason why the measured peak settlement \( S \) is lower than the simulated peak settlement: during the Beiheng shield tunnel underpassing, the ground loss rate \( \rho \) was ~0.3%, lower than the ground loss rate \( \rho = 0.5\% \) of data simulation.

6. Conclusions

The Midas GTS finite element analysis software was used herein to analyze the optimal clearance distance of super-large-diameter shield tunnel underpassing the existing metro tunnel in the soft soil area and relation between peak settlement and ground loss rate. Conclusions thus drawn:

(1) The peak settlement \( S \) and underpass clearance distance \( h \) of existing metro tunnel present a logarithmic relation, conforming to the formula \( S = -8.087 \ln(h) + 31.716 \).

(2) In case of underpass clearance distance \( h = 4.3 \pm 14.7 \) m, the peak settlement \( S \) of the existing metro tunnel is 20~10 mm. In case of underpass clearance distance \( h = 8.0 \) m, the peak settlement \( S \) of the existing metro tunnel shows significant response to the variation of underpass clearance distance \( h \).

(3) Therefore, it’s more proper for the underpass clearance distance \( h \) set at 4.3~8.0 m. Besides, in consideration of the existing metro tunnel safety, it’s more proper for the peak settlement \( S \) set at 15 mm. Therefore, the optimal underpass clearance distance \( h \) is 7.0~8.0 m.

(4) The ground loss rate \( \rho \) and the tunnel peak settlement \( S \) of the existing tunnel was linear, with the slope= 2.795 > 1. It proved that the tunnel peak settlement \( S \) of the existing tunnel was significantly influenced by the ground loss rate \( \rho \). Therefore, it’s quite reasonable to take the ground loss rate \( \rho \) as the evaluation indicator and control requirement for crossing construction.
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