Study on influence characteristics of shield tunnel depth and spacing on settlement in clay strata

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Abstract. The surrounding ground disturbance and surface settlement induced by shield construction are the key problems of tunnelling control and necessary to be studied. Taking the shield tunnel project of Beijing Subway Line 14 as the research background, this paper studies the influence of tunnel spacing and depth on surface settlement distribution by numerical simulation method, and analyzes the relationship between the two factors and maximum settlement. The results indicate that the increase of tunnel depth or tunnel spacing leads to the decrease of the maximum settlement and the settlement reduction rate increases. With the increase of tunnel depth, the settlement trough presents approximately symmetrical distribution, and the symmetry axis is inclined to the first tunnel. With the increase of tunnel spacing, the superposition effect of twin tunnel excavation decreases, and the settlement trough transits from U-shaped to W-shaped with the maximum settlement decreasing relatively from single peak to double peaks. Also, the tunnel depth or spacing is highly correlated with the maximum settlement in a certain range, and the tunnel depth has a stronger linear correlation than the tunnel spacing. The research results provide certain theoretical guidance and references for the prediction of ground deformation and settlement control of shield construction.

1. Introduction

The ground settlement caused by shield construction varies obviously in different geological and construction conditions. With regard to the common engineering problems, the influencing factors of ground settlement are mainly divided into construction, management and geological factors. Among them, the formal two factors can be realized by improving the construction management level while is difficult to calculate with the model, and the factors such as tunnel depth and tunnel spacing can be studied by means of numerical simulation. The research on these factors is necessary to the proposal of settlement control solutions in practical engineering. Many scholars have carried out detailed studies on the influencing factors of shield construction [1-4], and proposed extensive prediction models of ground settlement based on theoretical derivation and numerical simulation. Qiu et al. [9] adopted the combined methods of theoretical method, numerical simulation and field measurement to analyze the factors such as tunnel spacing, tunnel depth and internal friction angle, and studied the disturbance range, influencing factors and distribution characteristics of ground settlement and deformation induced by twin tunnel construction. Chen et al. [10] studied the calculation method of three-dimensional soil settlement caused
by ground loss in the construction of horizontal parallel twin tunnels based on Peck's formula. Zhao et al. [11] used numerical simulation method to analyze the surface settlement affected by the influencing factors such as layout of twin tunnels and grouting. Guo [12] studied the surface settlement and influence factors of several tunnel projects by numerical simulation analysis. In addition, many other researchers also investigated relevant researches on settlement influencing factors [13-15].

Based on the engineering background in Beijing Subway Line 14, this paper studies the influence characteristics and settlement reduction effect on the settlement trough by changing the tunnel depth and tunnel spacing, aiming to provide certain guidance for the tunnel parameter layout and settlement control in shield tunnel construction.

2. Engineering background

The ground settlement monitoring site of a certain section in Beijing Subway Line 14 is selected as the research background. The site is located in the plot to be developed, which is surrounded by walls and less affected by external conditions. The overburden thickness of the section is about 7.8 to 17.4m. According to the geological survey data, the crossing strata include silty clay layer, clay, silt, silty sand, silty clay and pebble. The strata are relatively uniform, mainly composed of silt and silty clay. The buried depth of tunnel vault is 11m, and the tunnel spacing is 11m. The right tunnel is the first excavated tunnel, and the left is the second.

3. Model establishment and parameter setting

In this paper, FLAC3D numerical simulation is applied to study the influence of tunnel depth and tunnel spacing on ground displacement. As different conditions need to be changed in the simulation, the initial modeling is briefly described at first. Along the direction of tunnel excavation, the grid length is 96m (i.e. 80 segments). The excavation is along the Y -axis direction. In the horizontal direction (perpendicular to the tunnel), the distance from the tunnel center is 35.5m, i.e. over 5 times of the tunnel diameter ($D$). In the vertical direction, the bottom is 25.5m (about 4$D$) away from the tunnel center. The overlying soil thickness and the tunnel spacing are both 11m. The model size is 82m × 96m × 36.6m (width × length × height), as shown in Fig. 1. The Mohr-Coulomb constitutive model is adopted for the soil, and the element dead-live method is used for excavation. In order to eliminate the influence of boundary effect, the settlement values caused by the excavation of the first two segments are cleared, and the data are recorded from the third segment. According to the actual situation, the soils above the two tunnels are simplified into different forms, and the continuous advance of the shield is simplified as a discontinuous step-by-step jump forward.

![Figure 1. Establishment of FLAC3D numerical model (FT: first tunnel; ST: second tunnel)](image)

On the basis of the initial working conditions, the distribution characteristics of surface settlement under six conditions of tunnel depths (11m, 16m, 21m) and tunnel spacings (11m, 17m, 23m) are studied by changing the corresponding factors, respectively. The schematic diagrams of simulated working conditions are shown in Figs. 2 and 3.
4. Analysis of simulation results

4.1. Influence of different tunnel depths on ground settlement

The surface monitoring points are selected to analyze the distribution of settlement troughs under three different tunnel depth conditions (the tunnel spacing is fixed as 11m), as shown in Fig.4. It can be concluded from Fig.4 that:

(1) With the increase of tunnel depth (11m, 16m, 21m), the maximum settlements of settlement troughs decrease in turn (-26.7mm, -21.5mm, -18.1mm, respectively). Compared with the settlement under the condition of 11m depth, the settlement reduction effect gradually increases (19%, 32%) at each increment of 5m in depth.

(2) The settlement troughs induced by twin tunnel excavation present approximately symmetrical characteristics, and the symmetry axis is inclined to the first tunnel, that is, located at the side line of the first tunnel.

(3) Under the condition of tunnel spacing of 11m, the settlement troughs of twin tunnel excavation are U-shaped, and only maximum settlement of single peak exists.
Summarize the effects of the above three conditions and carry out the regression analysis of the relationship between the depth-diameter ratio \( (H/D) \) and the maximum settlement, and the results are shown in Table 1 and Fig.5, respectively. The following regression equation is obtained:

\[
s_{\text{max}} = 5.0737 \frac{H}{D} - 35.63
\]  

Table 1. Simulation results under different tunnel depths

| Tunnel depth \( H/m \) | Depth-diameter ratio \( H/D \) | Depth increase proportion | Maximum settlement/mm | Settlement reduction ratio |
|------------------------|-------------------------------|--------------------------|-----------------------|--------------------------|
| 11                     | 1.8                           | /                        | -26.7                 | /                        |
| 16                     | 2.7                           | 45.40%                   | -21.5                 | 19%                      |
| 21                     | 2.5                           | 90.90%                   | -18.1                 | 32%                      |

Where \( s_{\text{max}} \) is the maximum settlement (unit: mm); \( H \) is the tunnel depth (m); \( D \) is the tunnel diameter (m). In the fitting formula, \( 1.8 < H/D < 2.5 \), within this range, the correlation coefficient \( R^2 \) is 0.9926 with high linear correlation degree, which indicates that depth-diameter ratio \( (H/D) \) and the maximum settlement have a high correlation linear relationship in a certain range.

4.2. Influence of different tunnel spacings on ground settlement

Similarly, select the surface monitoring points to analyze the settlement distribution under three different tunnel spacing conditions (the tunnel depth is fixed as 11m), as shown in Fig.6. It can be summarized from Fig.6 that:

1. With the increase of tunnel spacing (11m, 17m, 23m), the maximum settlements decrease, respectively (-26.7mm, -16.8mm, -15.3mm). Compared with the settlement under the condition of 11m depth, the settlement reduction effect increases gradually (37%, 43%) at each increment of 6m in spacing.

2. The settlement troughs gradually change from approximate symmetry to obvious asymmetry with the increase of tunnel spacing, and the position of symmetry axis moves with the maximum settlement deviating to the first tunnel.

3. With the increase of tunnel spacing, the superposition effect of twin tunnel excavation decreases, and the settlement trough turns from U-shaped to W-shaped. The maximum settlement decreases from single peak to double peaks.

Figure 6. Settlement troughs under different tunnel spacing conditions
The settlement reduction effects of the above three different tunnel spacing conditions are summarized in Table 2. Also, the regression analysis of the relationship between spacing-diameter ratio ($L/D$) and the maximum settlement and settlement trough width-diameter ratio ($W/D$) is carried out. The results are shown in Fig.7, and the regression formula is as below:

$$s_{\text{max}} = 5.7 \frac{L}{D} - 35.75$$  

(2)

$$W/D = 0.8333 \frac{H}{D} + 4.0833$$  

(3)

**Table 2.** Simulation results under different tunnel spacings

| Tunnel spacing | $L/D$ | Spacing increase proportion | Maximum settlement/mm | Settlement reduction ratio | Settlement trough width $W$/m | $W/D$ |
|----------------|-------|-----------------------------|------------------------|---------------------------|-------------------------------|-------|
| 11             | 1.8   | /                           | -26.7                  | /                         | 34                            | 5.7   |
| 17             | 2.8   | 54.50%                      | -16.8                  | 37%                       | 38                            | 6.3   |
| 23             | 3.8   | 109%                        | -15.3                  | 43%                       | 44                            | 7.3   |

Where $L$ is the tunnel spacing (unit: mm); $W$ is settlement trough width (m). In the two formulas, $1.8 < L/D < 3.8$. Within this range, the correlation coefficients $R^2$ are 0.8468 and 0.9868, respectively, which indicates that the spacing-diameter ratio ($L/D$) is both linearly correlated with the maximum settlement and the width-diameter ratio ($W/D$). Compared with spacing-diameter ratio ($L/D$), the depth-diameter ratio ($H/D$) has a higher linear correlation with the maximum settlement. This provides a certain theoretical basis for the settlement control of shield tunnel construction and the layout of tunnel parameters.

**5. Conclusion**

Based on the study of the distribution characteristics of surface settlements under different tunnel depth and tunnel spacing conditions, the correlations between the two factors and the maximum settlement are analyzed, and main conclusions are drawn as follows.

1. The increase of tunnel depth or tunnel spacing can both achieve the effect of reducing settlement, and the influence of the two factors on the characteristics of settlement trough has obvious difference. The increase of tunnel depths does not affect the approximate symmetry of the settlement trough within the given tunnel spacing. The symmetry axis is inclined to the first tunnel, and the maximum settlement has only single peak.

2. With the increase of tunnel spacing, the shape of settlement trough changes from U-shaped to W-shaped, and the excavation superposition effect of the two tunnels decreases. The maximum settlement decreases relatively from single peak to double peak shape.
(3) Tunnel depth and tunnel spacing are both linearly correlated with the maximum settlement (or settlement trough width). Compared with tunnel spacing, tunnel depth is more linearly correlated with the maximum settlement.

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