Research on Numerical Simulation of Soft Soil Foundation Reinforcement during the Process of Under-Crossing Subway Shield Tunnel

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Abstract: The disturbance of shield construction in coastal soft soil area poses a threat to the use and even safety of adjacent municipal transportation facilities. In order to study the influence of under-crossing shield construction on municipal transportation facilities in soft soil area, taking a practical project as an example, the author adopted numerical analysis method to conduct a comparative study of the influence of foundation reinforcement on under-crossing shield open-cut tunnels and bridges. The results show that for open-cut tunnels and bridges, foundation reinforcement can greatly reduce the deformation and internal force of the structure after under-crossing shield. At the same time, different reinforcement depths and methods will also lead to different results. The full reinforcement of 2 meters is obviously deeper than that of 3 meters, and strip-shaped reinforcement with 6-meter spacing has worse performance. Determining a reasonable reinforcement depth is of great significance for saving costs.

1. Introduction

In subway tunnel construction, shield method has gradually become the main choice of urban subway construction because it has less disturbance to the soil around the tunnel and there is no need to demolish existing buildings (structures) and underground structures. Many scholars have studied the deformation of existing buildings caused by under-crossing shield tunnel using methods such as measured data, theoretical and numerical research, and experimental simulation, and obtained many research results[1]-[3]. Mair et al.[4] pointed out that the ground traverse settlement trough caused by single-bore shield tunnel construction basically obeys normal distribution. Ng et al.[5]-[6] used three-dimensional centrifugal model test and finite element back analysis method to study the stress transfer mechanism of the upper perpendicularly crossing tunnel during the excavation of a new tunnel in sandy soil stratum and the influence of the ratio of tunnel spacing to tunnel diameter (P/D) on the interaction between two perpendicularly overlapping tunnels. Ma Shaokun et al.[7] considering the fact that tunnel excavation has adverse effects on the pile foundation of adjacent buildings, conducted centrifugal model tests concerning the influence of tunnels at different positions on pile groups, and
analyzed the variation laws of ground settlement, additional settlement at the top of the pile, additional bending moment and additional axial force caused by tunnel excavation.

Although the previous research results are of great significance for guiding engineering practice, for the soft soil areas along the coast of Jiangsu and Zhejiang provinces, there are unfavorable factors such as high groundwater level, and soil being soft with poor mechanical properties. The disturbance of shield construction leads to complex loading and unloading mechanical behavior of adjacent soil, changes the stress state of soil, and causes displacement of surface and deep soil in varying degrees. Once the shield tunnel is adjacent to or directly underneath the municipal transportation facilities, or they obliquely intersect with each other, the construction process will pose a threat to the use and even safety of buildings (structures). Before the implementation of the project, the insulating and protecting measures of foundation reinforcement are often adopted in the municipal transportation infrastructure projects pre-constructed. Through the soil reinforcement of the passive area in the foundation pit, the deformation of the upper foundation soil caused by the shield tunnel can be reduced \cite{8}-\cite{10}. Taking the municipal open-cut tunnel and bridge projects as an example, this paper conducts comparative studies of the influence of different reinforcement parameters on municipal tunnels and bridges, and forms a set of soft soil reinforcement theories which are economically efficient and with less influence in the later period, better ensuring the safety of existing structures. It is of great significance for the safe and smooth construction of under-crossing subway tunnels.

2. Influence of Under-Crossing Subway Shield Tunnel Construction on Existing Tunnels and Foundation Soil

The shield section of a subway line is planned to overlap the open-cut section of an under-crossing municipal tunnel for a long distance. The length of the overlapping section is about 750m, and the minimum clear distance between the overlapping subway section and the tunnel floor is only 3.4 m.

2.1 Establishment of Numerical Model

Using FLAC3D software for static calculation analysis, the three-dimensional numerical model is established as shown in Fig 1. The numerical model is 60m in X direction, 50m in Y direction and 30m in Z direction (below ground level).

![Fig 1 Numerical model](image)

In the calculation, the soil adopts Mohr-Coulomb constitutive model, and the parameters are shown in Table 1. The tunnel structure adopts elastic constitutive model and is simulated by shell element. The parameters are shown in Table 2. The reinforcement designs and parameters of the upper existing tunnel foundation are shown in Table 3. The horizontally fixed boundary is used around the model to limit its normal displacement, the vertically fixed boundary is used at the bottom to limit its displacement at the direction perpendicular to the ground, and the free boundary is used at the top.

| Number | Soil type                  | \( \gamma \)/kN/m\(^3\) | \( E \)/Mpa | \( \nu \)  | \( c \)/kPa | \( \phi \)/\(^\circ\) |
|--------|----------------------------|---------------------------|--------------|----------|-------------|----------------|
| 1      | Miscellaneous fill         | 18                        | 10           | 0.35     | 8           | 8             |
| 2      | Muddy clay                 | 16.91                     | 1.5          | 0.3      | 11.9        | 7.2           |
| 3      | Fully weathered sandy mudstone | 19.8                   | 10           | 0.28     | 28.3        | 15            |
Table 2 Parameters of tunnel structure

| Elements type         | ρ/kg/m³ | E/Mpa   | ν  |
|-----------------------|---------|---------|----|
| Structural shell element | 2700    | 40000   | 0.25 |

Table 3 Reinforcement scheme and parameters of existing tunnel soft soil foundation

| Number | Reinforcement scheme                        | E/MPa | ν   |
|--------|-------------------------------------------|-------|-----|
| 1      | Scheme①: Unreinforcement                  | 4.76  | 0.3 |
| 2      | Scheme②-1: Cement soil mixing pile + Full reinforcement + Reinforced depth 2m | 85    | 0.29 |
| 3      | Scheme②-2: Cement soil mixing pile + Full reinforcement + Reinforced depth 3m | 86    | 0.29 |
| 4      | Scheme③-1: Cement soil mixing pile + Skirt edge , Strip reinforcement(interval 3m) + Reinforced depth 3m | 54    | 0.3 |
| 5      | Scheme③-2: Cement soil mixing pile + Skirt edge , Strip reinforcement(interval 6m) + Reinforced depth 3m | 48    | 0.3 |

2.2 Influence of Different Reinforcement Designs on Internal Force and Displacement of Upper Tunnels

Fig 2 shows the extreme value of internal force of the upper tunnel before and after reinforcement. Among them, the internal force is reduced the most when the ②-2 design is adopted. By comparing the effects of the four reinforcement designs, it can be concluded that the reinforcement effect of the design ②-2 is the best, followed by ③-1, then ③-2, and finally ②-1.

Fig 3 respectively show the displacement of the upper tunnel in Z direction in different scenarios. In design ①, without reinforcement, the displacement in Z direction is -39.072 ~ 86.753 mm. The larger settlement is located in the overlapping section of the upper and lower tunnels, and the displacement is increased compared with that with reinforcement. In design ②-1, after reinforcement, the displacement of the upper tunnel in Z direction is -34.557 ~ 56.107 mm. In design ②-2, after
reinforcement, the displacement of the upper tunnel in Z direction is -36.533 ~ 38.935 mm. In design ③-1, after reinforcement, the displacement of the upper tunnel in Z direction is -38.110 ~ 42.472 mm. The larger values of settlement displacement in Z direction of the upper tunnel obtained by the four reinforcement designs are all located in the overlapping section of the upper and lower tunnels.

Fig 3 The displacement of the upper tunnel after the subway tunnel shield is undercut: (a) Z- displacement of the reinforcement scheme ①; (b) Z- displacement of the reinforcement scheme ②-1; (c) Z- displacement of the reinforcement scheme ②-2; (d) Z- displacement of the reinforcement scheme ③-1; (e) Z- displacement of the reinforcement scheme ③-2

Fig 4 shows the extreme value of displacement of the upper tunnel before and after reinforcement treatment. By comparing the displacement of the upper tunnel in Z direction after reinforcement, it can be seen that the soil reinforcement underneath the upper tunnel can effectively reduce the vertical displacement of the structure. It can be seen from the figure that the reinforcement design has the greatest effect on the vertical displacement of the structure. For the displacement in Z direction, adopting the design ②-2, it can be reduced by 47.818 mm, with design ③-1, it can be reduced by 44.281 mm, with design ③-2, it can be reduced by 43.683 mm, and with design ②-1, it can be reduced by 30.646 mm. It can be concluded that the design ②-2 has the greatest effect on reducing the vertical displacement of the structure, while the design ②-1 has the least effect. Therefore, in terms of the displacement of the upper tunnel after and before reinforcement, the design ②-2 can achieve the best effect.
Fig 4  Z-displacement of upper tunnel before and after reinforcement treatment

3. Influence of Under-Crossing Subway Shield Tunnel Construction on Existing Bridge and Foundation Soil

The left half of a municipal bridge is located above the shield section of a subway line under construction, and the pile foundation layout should meet the relevant requirements of the subway. Left half piers adopt pile foundation, with the clear distance between pile foundation and subway shield of 1.8 m-1.9m.

3.1 Establishment of Numerical Model

Plaxis3D software is used for numerical simulation, and the model is shown in Fig 5. The left half of the bridge is modeled and the influence of shield tunnel excavation process on bridge pile foundation is observed. The numerical model is 20m in X direction, 40m in Y direction and 41m in Z direction (below ground level).

In the calculation, the soil adopts Mohr-Coulomb constitutive model. The reinforcement design of bridge foundation is shown in Table 4. The cement mixing pile for foundation reinforcement is simulated by pile model. The parameters are shown in Table 5.

| Number | Reinforcement scheme                        |
|--------|---------------------------------------------|
| 1      | Scheme①: Unreinforcement                    |
|        | Scheme②: Reinforced dense area + Non-reinforced dense area |
| 2      | Non-reinforced dense area: (Pile length 8m, Pile spacing 1.2m, Pile diameter 0.5m) |
|        | Reinforced dense area: (Pile length 15m, Pile spacing 1m, Pile diameter 0.5m) |
Table 5 Parameters of cement mixing pile

|                         | Pile length /m | Pile spacing /m | E/MPa | Area replacement rate/% | Resistance force of side friction/kN/m |
|-------------------------|----------------|-----------------|-------|-------------------------|--------------------------------------|
| Cement mixing pile 1    | 8              | 1.0             | 150   | 15.8                    | 98                                   |
| Cement mixing pile 2    | 15             | 1.2             | 150   | 22.7                    | 240                                  |

The bridge pile foundation used the concrete C30, and elasticity modulus E of \(3.00 \times 10^4\) N/mm\(^2\). C40, and the pile caps within the scope of the subway tunnel used the concrete C40 and elastic modulus E of \(3.15 \times 10^4\) N/mm\(^2\). The subway tunnel segment has an outside diameter of 6200mm, an inside diameter of 5500mm, and thickness of 350mm. The elevation of the upper part of the tunnel is -15. 295 m, and that of the lower part of the tunnel is -21. 495 m. The model is established according to the dimension of the tunnel. After the shape of the model is ready, the corresponding material is assigned a value. The segment and lining of the tunnel are simulated by creating a plate with thickness of 0.35 m and the material properties are linear and isotropic.

3.2 Calculation Results and Analysis

Total displacement \(U_z\) of pile cap is shown in Fig 6. The excavation of the tunnel will cause certain settlement of the pile cap, and at the same time, the soil above both sides of the tunnel will move horizontally towards the center line of the tunnel. It can be seen from the figure that the total displacement \(U_z\) of the pile cap when the foundation is not reinforced is between 7.231 cm and 8.680 cm, and the total displacement \(U_z\) of the pile cap after the foundation is reinforced is between 3.071 mm and 4.081 mm. After the foundation soil is reinforced, the deformation of the pile cap is greatly reduced, and the maximum vertical deformation is reduced from 8.68 cm before reinforcement to 4.081 mm after reinforcement.

![Fig 6](image)

Tunnel excavation will destroy the soil structure, cause deformation of the surrounding soil, and lead to the soil settlement in the vertical direction. When the soil is not reinforced, the settlement value of the soil is between 0 cm and 8.680 cm. After soil reinforcement, the settlement value of the soil is between 0.6746 and 8.556 mm. The details are shown in Fig.7. After the foundation soil is reinforced, the maximum vertical settlement of the soil is reduced from 8.68 cm before reinforcement to only 8.556 mm.
4. Conclusions

The main conclusions are as follows:

(1) The numerical simulation of different reinforcement measures of soft soil foundation in existing tunnels is carried out, and it is found that full reinforcement of 3-meter foundation using cement soil mixing pile has the best effect of reducing the internal force of the overlying structure, followed by 3-meter skirt and strip reinforcement (3-meter spacing), and finally the 2-meter full reinforcement. Therefore, it is of great significance to determine a reasonable reinforcement depth for saving engineering costs.

(2) Under the conditions of shield construction and operation, the areas with large internal forces in the upper tunnel are concentrated at the overlapping parts of the tunnels. After the soft soil foundation of the tunnel is reinforced with cement mixing piles, the axial force, bending moment and shearing force of the upper tunnel structure are significantly reduced. In addition, the displacement in Z direction is also reduced, and the axial force and vertical displacement are improved the most.

(3) The construction of the shield tunnel will lead to the settlement of the surrounding soil, and the soil above the tunnel will form a natural arch. Three-dimensional numerical simulation shows that the maximum value of vertical displacement reaches 8.68 cm when there is no reinforcement, and the vertical settlement is reduced to 4.86 mm after reinforcement.

(4) The construction of under-crossing shield tunnel will lead to settlement and deformation of the pile cap of the upper bridge. Three-dimensional numerical simulation shows that the average vertical deformation of the pile cap caused by tunnel excavation under the condition of unreinforced foundation soil is 8.68 mm, and the average vertical deformation of the pile cap is reduced to 2.21 mm. At the same time, the settlement of the pile cap at different locations is relatively consistent, and there are hardly any differential settlements.

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