Prediction of ground settlement on shielded water-rich sand layer considering groundwater level and tunnel depth

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Abstract. In order to research the effect of different groundwater level and tunnel depth on the ground settlement law for the shield construction of the water-rich sand layer, monitoring data of Fuzhou Metro Line 6 project is adopted and analyzed. The finite element software Plaxis 3D is used to carry out the numerical simulation of the project. Using the "activate" and "deactivate" functions of Plaxis 3D finite element software, the jack thrust, grouting pressure, face pressure, shield machine advancement and splicing of the segment are simulated. The calculation results in terms of vertical displacement of ground surface are in good agreement with the actual monitoring data. Using this numerical simulation method, under the combined action of different groundwater level and different tunnel depth, the ground settlement law of shield in the water-rich sand layer is studied, and the following conclusions are drawn: the shallower the groundwater level in the same tunnel burial depth, the greater the surface settlement, the greater the buried depth of the tunnel and the smaller the surface settlement.

1. Introduction

Subway construction in Yangtze River Delta region, the Pearl River Delta region, the Bohai Rim region and other major cities is booming[1]. Shield construction has the most extensive due to its high degree of automation, high construction safety, fast construction speed and little impact on the surrounding environment[2]. However, the impact on the ground surface is unavoidable during the construction process, especially in the water-rich sand layer due to the low bearing capacity, large permeability coefficient and poor self-stability[3][4]. Therefore, the risk of ground surface subsidence and excessive settlement is likely to occur during the construction of the shield[5]. In order to ensure safety, it is necessary to predict the ground settlement of the water-rich sand layer. At present, some researchers have studied the ground settlement of water-rich sand layers caused by shield construction. According to the shield construction monitoring data of Xi'an rich water sand layer, the Peck empirical formula is improved, and it is suitable to predict the surface settlement of the water-rich layer caused by shield construction in Xi'an[6]. Considering the Biot consolidation theory, the constitutive relation of soil is extended to viscoelasticity and plasticity, and the fluid-solid coupling calculation is carried out. The numerical simulation method is used to predict the ground settlement, and the conclusion that the settlement between the two axes of the double-line tunnel shield is the largest is obtained[7]. Zhang Yuanrong et al. considered the fluid-solid coupling effect of the water-rich sand layer, numerically
simulated the shield construction in the water-rich sand layer, analyzed the law of surface subsidence and pore water pressure, and compared it with the on-site monitoring data[8].

The methods for predicting surface settlement mainly include empirical formula method, analytical method and numerical method[6][10]. The existing literature indicates that numerical methods have been increasingly applied to surface settlement prediction[7]. For shield construction in water-rich sand layers, due to the complexity of engineering geological conditions, the depth of groundwater in different sections tends to be different, and the depth of different groundwater levels will affect the consolidation degree of the soil layer, and the settlement of the surface will also change. The interval tunnel often has a certain slope, which results in different depths of tunnels at different locations. The buried depth of the tunnel is also an important factor affecting surface settlement. However, the influence of water level and tunnel depth on surface settlement is rarely considered. Therefore, based on the Fuzhou Metro Line 6 project, the numerical simulation method is used to research the combined action of two factors, namely the depth of the water level and the depth of the tunnel, on the ground settlement. The conclusion can be used for the surface settlement prediction caused by the shield construction of similar projects and give construction guidance.

2. Project review
The interval tunnel of Fuzhou Metro Line 6 Hujing Station ~ Wanshou Station departing from the Hujing Station, lays along the Daoqing Road, reaches the Wanshou Station at the intersection with the Provincial Highway 201, and there are farmland, ponds and a small number of houses along the line, as shown in Figure 1. The mileage is XK29+939.853~XK30+860.731, the length is 920.928m, the maximum tunnel longitudinal slope is 23%, and the covering soil is about 6.5m~14.1m. The Huwan section is mainly filled with soil, fine sand, medium-fine sand, completely decomposed granite, and heavily weathered granite. The shield mainly passes through the fine sand layer and the medium-fine sand layer, and the geological section is shown in Figure 2. The interval tunnel is located on the south bank of coastal plain in the Minjiang Basin. The surface water is developed, and there are a large number of fish ponds and small rivers. The surface water and groundwater have a unified groundwater level with a shallow depth ranging from 0.11m~6.89m.

![Figure 1. planar graph of interval tunnel of Hujing Station-Wanshou Station](image1)

![Figure 2. Profile view of interval tunnel of Hujing Station-Wanshou Station](image2)
3. On-site monitoring data and analysis of surface settlement
The shield construction starts from Wanshou Station, and reaches the Hujing Station. Shield tunneling rate is 8m/day. Only the monitoring data of the right line is analyzed. The vertical surface settlement monitoring points of the Huwan section are arranged every 12m along the axial direction of shield tunnel, as the figure 3 shows.

![Figure 3. planar graph of Monitoring points](image)

The lateral monitoring points are perpendicular to the tunnel axis, and the distance between two sections for monitoring points is 90m. Among them, 4, 6, 7, 8, 9, 10, and 11 points are monitored for the up line, and 1, 2, 3, 4, 5, 6, and 8 points are monitored for the downline. This article only analyzes up line monitoring data.

![Figure 4. Horizontal monitoring points layout](image)

4. Numerical Simulation
4.1. Model basic information and material parameters
According to the actual engineering characteristics of the Huwan section, the shield model of the water-rich sand layer as shown in the figure 5 is established. The length × width × height of the model is 80m × 60m × 30m, which can basically eliminates the influence of the boundary on the calculation results.
The hardening soil model considering shear hardening and compression hardening is used to simulate the water-rich sand layer, and the model adopt a linear elastic constitutive model for the concrete and shield machine plates. Material parameters are shown in the tables below.

Table 1. Hardening soil model material parameters

| Soil            | Natural gravity $kN/m^3$ | Saturated gravity $kN/m^3$ | Young's modulus $kN/m^2$ | Cohesion $kN/m^2$ | Internal friction angle $^\circ$ | Secant modulus $MN/m^2$ | Tangent modulus $MN/m^2$ | Unloading and reloading modulus $MN/m^2$ | Dilatancy angle $^\circ$ |
|-----------------|--------------------------|-----------------------------|--------------------------|-------------------|---------------------------------|-------------------------|----------------------------|-------------------------------------|------------------------|
| Filling         | 15                       | 18                          | 15                       | 12                | 5                               | 5                       | 5                         | 15                                  | 0                      |
| Powdery fine sand | 18                       | 19                          | 5                        | 18                | 7                               | 7                       | 7                         | 21                                  | 2                      |
| Medium fine sand | 18                       | 19                          | 6                        | 20                | 7                               | 7                       | 7                         | 21                                  | 3                      |

Table 2. Other material parameters

| material                     | Natural gravity $kN/m^3$ | Saturated gravity $kN/m^3$ | Young's modulus $kN/m^2$ | Cohesion $kN/m^2$ | Friction angle $^\circ$ | Poisson's ratio |
|------------------------------|--------------------------|-----------------------------|--------------------------|-------------------|-------------------------|-----------------|
| Fully weathered granite      | 19                       | 20                          | 3e4                      | 23                | 24                      | 0.33            |
| Concrete                     | 25                       | 3.1e7                       |                          |                   |                         | 0.1             |
| Shield machine board         | 120                      | 2.3e7                       |                          |                   |                         | 0.1             |
4.2. Shield Tunneling Process Simulation

The displacement in the X direction at the left and right sides are zero, and the displacement in the Y direction at the front and rear sides are also. The upper surface is a free boundary, the lower surface limits the Z direction displacement, and the front, rear, left and right and lower surfaces are both set to be impervious. The buried depth of the tunnel is simulated by 6m, 8m, 10m, 12m, 14m and 16m respectively. The groundwater level is simulated by -2m, -4m, -6m, -8m and -10m respectively. The outer diameter of the shield is 6.2m. The inside diameter of the shield is 5.5m, the tube piece thickness is 0.35m, 1.2m per ring, a total of 50 rings. Using the "activate" and "deactivate" functions of Plaxis 3D finite element software, the jack thrust, grouting pressure, face pressure, shield machine advancement and splicing of the segment are simulated.

4.3. Field monitoring data and numerical simulation results analysis

1. Tunnel longitudinal monitoring points analysis

In the monitoring scheme, the tunnel depth of SDC90 monitoring point is about 10m, and the groundwater level is -0.11m. Therefore, the monitoring point with 10m depth and 0m water level in the numerical simulation is selected, which shows that the numerical simulation result is in good agreement with the field monitoring data. It can be seen from the graph 6 that: 1. Before the shield machine reaches the monitoring point, because the cohesion of sand is very small and the groundwater level is very shallow in the water-rich sand layer, with the advance of the shield machine, the pore water pressure in front of the head of shield machine increases, resulting in a little ground settlement rise or subsidence; 2. When the shield machine reaching the monitoring point, because in the water-rich sand layer and the large soil permeability coefficient, the grouting pressure is difficult to maintain the design value. So it will bring too much disturbance to the soil layer above the tunnel face and cause too much soil loss. The ground settlement will increase rapidly and basically to reach the maximum settlement. Therefore, the ground settlement should be controlled in this process, and the grouting volume should be increased to reduce it; 3. After shield machine passing the monitoring point, the ground settlement will gradually increase a little, but because of the shallow groundwater level in the water-rich sand layer, the tunnel will still float 3-5 mm due to buoyancy.

![Figure 6. Ground settlement of longitudinal monitoring points](image)

2. Tunnel lateral monitoring points analysis

The cross section corresponding to the tunnel depth of about 10 and the groundwater level of -0.11 m was selected for analysis. The settlement tank formed by the on-site monitoring data is smaller than...
the settlement tank formed by the numerical simulation results, and the maximum ground settlement is consistent.

![Figure 7. Ground settlement of lateral monitoring points](image)

3. Influence of groundwater level on ground settlement

In the water-rich sand environment by shield constructing, the influence of groundwater level on the ground subsidence is very large. The groundwater level is 0m, -2m, -4m, -6m, -8m, and -10m. 6 working conditions were analyzed. It can be seen from the figure 8 that the deeper the groundwater level lead to the smaller the maximum ground settlement, and the shallower the water level lead to the greater the impact on the ground settlement.

![Figure 8. Surface subsidence under different groundwater levels](image)

4. Influence of tunnel depth on ground settlement

The same groundwater level is selected as 0m, and the six types of working conditions of tunnel depths of -6m, -8m, -10m, -12m, -14m, and -16m are analyzed. It can be known that the greater the buried depth of the tunnel, the ground settlement value smaller, and the smaller the tunnel depth, the greater the impact on ground settlement.
5. Conclusion
Through the analysis of the monitoring data of the Fuzhou Metro Line 6 project in the water-rich sand layer area, and the finite element numerical simulation analysis of the different groundwater level and the depth of different tunnels, the ground settlement law of water-rich sand shield by the combination of the groundwater level and the tunnel depth to the ground settlement is studied. The following conclusions are drawn:

1. Through the analysis of the field measured data, it can be found that in the water-rich sand layer, the ground settlement curve can be divided into three stages: the upper and lower floating before the shield face, the steep subsidence above the shield face, and the small amount of floating on the surface after the shield construction. It is suggested that construction in this type of stratum should pay attention to controlling the settlement of the ground above the shield face.

2. By analyzing the shield law in the water-rich sand layer with groundwater level 0m, -2m, -4m, -6m, -8m, -10m, the groundwater level is shallower and the surface settlement is larger.

3. Through the analysis of the shield law of the water-rich sand layer with the buried depth of 6m, 8m, 10m, 12m, 14m and 16m, the deeper the buried depth of the tunnel, the smaller the ground settlement, the smaller the floating amount on the surface when the shield is completed.

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