Effect of Shield Tunnel Construction on Surface Deformation in Changzhou

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Abstract. The test section of Changzhou North Railway Station of Rail Transit Line 1 is taken as the engineering background. It is before the shield tunnel passes through the Beijing-Shanghai high-speed railway. With software of PLAXIS 3D, the numerical simulation on surface deformation is conducted considering the influence of shield tunnelling, based on the M-C, HS and HSS model. The calculated results of the three models are compared with the monitoring data. It is shown that the HSS model is optimal. In addition, the applicability of 0.5% and 0.8% for the loss rate of shield tunnelling in Changzhou is studied. It is reasonable to adopt 0.5% stratum loss rate for general shield tunnel conditions. But, sometimes in order to consider the special conditions such as deviation rectification construction, stratum loss rate should be set at 0.8%.

1. Introduction
In the modern urban rail transit construction project, the shield construction method is widely used due to its advantages of safe excavation and lining, faster tunnelling speed, and full-automatic operation. During the excavation process, the excavation thrust provided by the jack during the excavation will exert pressure on the soil in front of the excavation route, causing the surface soil layer to rise; During the construction process of shield tunnelling, over-excavation of the head part in the direction of excavation will cause loss of ground and settlement of soil around the tunnel.

The research methods of the influence of shield excavation construction on the surrounding environment generally include empirical formula, theoretical research method, indoor model test method, and numerical calculation method of finite element software.

1.1. Empirical formula and theoretical research method
Under the influence of tunnel excavation construction, the most widely used theoretical study of surface settlement is the Peck formula method[1]. Peck studied and analyzed the engineering data and stratum subsidence monitoring data, and proposed that under the influence of tunnel excavation construction,
the settlement of the ground deformation is pseudo-normal distribution law, and the calculation formula for estimating the ground subsidence is given. Loganathan proposed the calculation model of "Equivalent Ground Loss Method" in 2001 [2], and improved the analytical solution by using the gap parameter, and obtained a more accurate analytical formula for calculating soil displacement. Based on the research results of Sagaseta, Jiang Yanliang used the mathematical integral theory calculation method to obtain the displacement distribution of the soil after the grouting of the shield machine [3-4].

1.2. Indoor model test method
Most of the theoretical methods can only get a simple two-dimensional solution, it is difficult to consider the three-dimensional effect, and the theoretical method is lack of accuracy due to the premise of a large number of assumptions. The model test method is mainly in the laboratory, through the similarity simulation experiment and centrifuge simulation experiment, some practical conclusions and formulas are obtained.

Qingshu Liu used the centrifugal model test to simulate the actual situation of the project in order to obtain the predicted surface settlement of the three-hole and three-line sections of the Shenzhen Metro [5].

1.2.1. Numerical simulation
Ding Chunlin studied the influence of subway tunnel construction on tunnel surrounding rock acceptance and ground deformation under the condition of stress relief by finite element software numerical calculation method [6].

Mroueh H studied the influence of the deformation of the building surface under different working conditions in the shield section during the construction of the shield by numerical simulation [7].

2. Constitutive model
Through a summary of a large number of engineering practices, the analysis can be concluded. In tunnel engineering, only a small part of the soil is plastically deformed. In most areas, most of the soil is in a state of small strain stress, and the strain is between 0.01% and 0.1%.

Based on the Mohr-Coulomb, HS and HS-Small soil constitutive model parameters of typical soil layers in Changzhou, this paper aims at the actual working conditions of the shield tunnel before the tunnel passes through the Beijing-Shanghai high-speed railway. The PLAXIS 3D is used to numerically simulate the influence of shield excavation on the deformation of the ground.

3. Project Overview
The engineering background of this paper is the test section of shield tunnel with similar engineering geology before the Huanghu Road Station-Longhutang Station of Changzhou Rail Transit Line 1 passes through the Beijing-Shanghai high-speed railway. According to the detailed geological survey report of this project, the basic parameters of the soil layer involved in the construction of this shield are shown in Table 1.

| Soil layer          | $\gamma' \text{ (kN/m}^3\text{)}$ | $c \text{ (kPa)}$ | $\phi' \text{ (°)}$ |
|---------------------|----------------------------------|-------------------|---------------------|
| ②_Susludge silty clay | 17.6                             | 19                | 6.1                 |
| ③_2 Silty clay      | 19.3                             | 49                | 13.3                |
| ③_3 Silty clay      | 18.9                             | 30                | 19.3                |
| ⑤_2 Silty sand      | 19.3                             | 4                 | 32.5                |
| ⑦_1 Clay            | 17.9                             | 23                | 11.1                |
| ⑦_2 Silty clay      | 19.2                             | 23                | 14.6                |

The ground vertical deformation measurement points of the shield tunnel test section are shown in Figure 1.
4. Numerical simulation of foundation pit excavation

4.1 Geometric model and calculation parameters

In this section, Plaxis3D is used to numerically simulate the actual working conditions of the shield construction in this test section. Three different soil constitutive models of M-C, HS and HSS were used to analyze the influence of shield excavation on surface settlement. According to the mutual empirical relationship between indoor soil test and small strain parameters of soil in engineering practice, the small strain parameters of soil used in this paper are shown in Table 2 below.

| Soil layer | $p_{\text{ref}}$/kPa | $G_{0\text{ref}}$/MPa | $E_{\text{red}}^\text{ref}$/MPa | $E_{\text{so}}^\text{ref}$/MPa | $E_{\text{ur}}^\text{ref}$/MPa | $\gamma_{0.7}$ |
|------------|---------------------|---------------------|-----------------------------|-----------------------------|-----------------------------|---------------|
| Clay       | 100                 | 50.0                | 4.8                         | 5.5                         | 17.5                        | 4.0×10^{-4}   |
| Sand       | 100                 | 112.0               | 12.9                        | 14.2                        | 45.0                        | 2.2×10^{-4}   |
| Silty clay | 100                 | 70.0                | 8.0                         | 8.0                         | 32.0                        | 3.0×10^{-4}   |

In the table:

- $p_{\text{ref}}$ -- reference pressure
- $E_{\text{so}}^\text{ref}$ -- three-axis drainage test secant stiffness under reference pressure
- $E_{\text{red}}^\text{ref}$ -- tangential stiffness of lateral line compression test under reference pressure
- $E_{\text{ur}}^\text{ref}$ -- Engineering strain unloading-reload stiffness under reference pressure
- $G_{0\text{ref}}$ -- Reference initial shear modulus
- $\gamma_{0.7}$ -- the shear strain when $G_s = 0.772G_0$

The shield construction in this project is mainly located in the silt layer, and the engineering performance is good, which is not easy to cause large loss of formation. Therefore, the loss rate of the formation in the numerical simulation of the actual working conditions is 0.5%. In order to consider the special circumstances such as rectification and construction, the numerical simulation of the 0.8% formation loss rate was also carried out.

In the numerical simulation calculation model of this paper, the completed tunnel of 10m is first defined, and the lining structure of the completed tunnel is simulated by the solid element. The steel plate material shield machine head uses the plate unit with normal stiffness and strength in the software to simulate over-excavation and formation loss by setting the line contraction of the excavation path in the excavation. Using the surface load that varies linearly with depth, the silo pressure and the tail grouting pressure of the excavation face are simulated. In the software simulation, when one part of the...
head part is hoisted forward, the grouting load is removed from the tail, and the last unit of the tail is set as the solid unit of the simulated lining. Repeatedly, the excavation process of the simulated shield construction, the parameters of the relevant materials are shown in Table 3, and the shield tunneling parameters are shown in Table 4.

Table 3. Parameters of materials

| Name               | $E$ (kN/m²) |
|--------------------|-------------|
| Shield machine head| 2.1E8       |
| Lining tunnel      | 3.15E7      |

Table 4. Shield machine tunneling parameters

| Name                   | Parameters               |
|------------------------|--------------------------|
| Chamber pressure       | 0.26 ~ 0.30 Mpa          |
| thrust force of the jack| 12000 ~ 16000 kN        |
| Turning speed of cutter head | 1 ~ 1.2 rpm       |
| Grouting pressure      | 0.28 ~ 0.38 Mpa          |

The groundwater level of this project is calculated by -0.5m. During the construction of the tunnel, all the water in the tunnel is considered for pumping. Because only the influence of shield excavation on surface settlement is considered in the test section, the symmetry geometric model can be used in this project, and half of the shield excavation is used to establish the calculation model. The calculation model and mesh division are shown in Figure 2.

4.2 Analysis of calculation results

4.2.1 Analysis of calculation results using soil M-C constitutive model.

The settlement of the soil layer calculated by the M-C constitutive model is shown in Figure 3. The comparison of surface settlement is shown in Figure 4.

It can be seen from Figure 4 that under the influence of shield tunnel construction, the calculation of surface settlement is similar to the actual monitoring curve, and the settlement of the ground deformation is consistent with the pseudo-normal distribution law under the influence of tunnel excavation proposed by Peck. However, the calculated maximum settlement of the tunnel is 17.68mm, which is much larger than the monitoring value of 5.44mm. The numerical calculation results cannot accurately reflect the engineering reality, and the prediction of the results of engineering monitoring lacks accuracy. It is indicated that the numerical calculation of the shield excavation construction cannot accurately reflect the actual situation by using the M-C soil constitutive model.

The change of surface settlement at the measuring point XD21 is shown in Figure 5.
It can be seen from Figure 5 that the trend of calculated value of the surface settlement is the same as the actual monitoring value. However, as the shield advances, the settlement value of the calculated point is far larger than the monitored value. From this point, it can be proved again that the calculated value of the soil settlement deformation depend on M-C model is very different with the actual value, can not accurately reflect the actual situation of the project.

4.2.2 Analysis of calculation results using soil HS constitutive model.

The comparison of surface settlement calculated by the HS constitutive model is shown in Figure 6. It can be seen from Figure 6 that the value calculated by the HS model is similar to the value calculated by the M-C model. The maximum settlement of the ground calculated by the HS model is 15.95mm, which is smaller than the 17.68mm calculated by the latter, but the difference from the monitored value is still large. The results of numerical calculations also fail to accurately reflect the actual project, and the prediction of the results of engineering monitoring lacks accuracy.

The change of surface settlement at the measuring point XD21 is shown in Figure 7.

It can be seen from Figure 7 that the calculated value is the same as the actual monitoring value, but with the forward advancement of the shield, the settlement value of the calculated point is far greater than the monitored value. So it can also be explained that the HS soil constitutive model is lack of accuracy.

4.2.3 Analysis of calculation results using soil HSS constitutive model.

The comparison of surface settlement calculated by the HS constitutive model is shown in Figure 8. After the shield tunnel passing through the soil layer, the soil layer above the tunnel will settle due to soil loss. The surface settlement curve caused by the shield tunnel construction is consistent with the theoretical Gaussian curve. It can be seen from the relationship between the monitoring values of the
surface subsidence and the calculated values at the XD21 section in the figure that the calculated data is in good agreement with the monitoring data, and the numerical calculation results can reflect the engineering reality more realistically. The maximum calculated settlement value of the surface is slightly larger than the monitored value, which should be adjusted accordingly in future engineering predictions to make a more accurate prediction analysis of the project.

Ground settlement at the XD21 point on the center line of the shield tunnel
The change of surface settlement at the measuring point XD21 is shown in Figure 9.

![Figure 8. Comparison of calculated value and measured value of ground surface settlement of HSS model](image)

![Figure 9. The ground surface settlement of XD21 of HSS M-C model](image)

It can be seen from Fig. 10 that the monitoring value of this point is the same as the change trend of the settlement value. The maximum settlement calculation value of the inspection point is 5.98mm, which is basically consistent with the maximum monitoring settlement value of 5.44mm at this point. Therefore, the applicability of the numerical simulation calculation of the HSS soil constitutive model in the shield construction project is proved again. In addition, during the forward excavation of the shield tunnel, the observation point XD21 is disturbed and produces a slight bulge. As the shield advances, the inspection site begins to settle and passes through the XD21 monitoring section at the end of the shield machine. That is, when the shield head passes through the inspection point and reaches 8.4 m, after the lining is completed, the settlement gradually converges. Then, as the shield moves forward, the surface settlement changes little, so the deformation of the section basically represents the situation after the tunnel passes through the section. The use of this rule in future monitoring can bring convenience to monitoring.

4.2.4 Comparative Analysis of Numerical Simulation of Three Soil Constitutive Models.
In order to compare the advantages and disadvantages of the three soil constitutive models more clearly and intuitively, the calculation results of the three soil constitutive models are integrated with the monitoring results as shown in Figure 10 and Figure11.

It can be more intuitively seen from Figure 11 and Figure12 that the HSS soil constitutive model is superior to the other two soil constitutive models, and the calculation results using the soil small strain constitutive model are closer to reality. This proves that the soil will be in a state of small strain stress under the influence of shield construction. It can be seen from the figure that the soil constitutive model is used to simulate the shield excavation construction, and the accuracy of the calculation results is ranked: HSS>HS>M-C.
4.2.5 Analysis of formation loss rate.

Referring to the summary and feedback analysis of existing construction experience, the 0.5% formation loss rate is taken as the value of normal construction. In order to prove the rationality of this value and also to consider the special circumstances such as rectification and construction, the ground deformation is analyzed when the formation loss rate is 0.8%.

The formation loss rate of the HSS soil constitutive model was 0.8%. The whole shield construction was simulated, and the settlement deformation at the monitoring surface was analyzed, and then compared with the monitoring data. The comparison is shown in Figure 12.

It can be seen from Fig. 12 that the calculated data obtained by using the 0.5% formation loss rate is more consistent with the surface monitoring settlement value. The calculated value obtained by using the 0.8% formation loss rate is larger than that of the surface monitoring, which indicates that the 0.5% formation loss rate is reasonable for the general shield construction conditions. However, in some cases, in order to consider special conditions such as rectification and construction, the formation loss rate needs to be set to 0.8%. The obtained settlement calculation data can also bring reference to the project. If the settlement data is too large, certain control measures can be taken in advance for the construction process to avoid engineering loss.

5. Conclusion

The calculated values of surface settlement calculated by three soil constitutive models of MC, HS and HSS are consistent with the theoretical Gaussian curve; The HSS soil constitutive model is used to simulate the surface settlement data and the monitoring value has a better agreement. The numerical calculation results can reflect the actual project reality. The maximum settlement value of the surface in the calculated data is slightly larger than the monitored value, which should be adjusted accordingly in future engineering predictions to make a more accurate prediction analysis of the project.
By examining the monitoring point XD21 along with the settlement variation analysis of the shield tunneling, it can be seen that after the shield section passes through the monitoring section and the lining is completed, the settlement of the point gradually converges, and then the surface settlement changes little as the shield moves forward. At this time, the deformation of the section basically represents the situation after the tunnel passes through the section.

In the process of shield construction, in order to consider special conditions such as rectification and construction, the formation loss will increase, and the shield construction simulation of 0.8% formation loss rate is also carried out, and the obtained results can also provide reference for construction.

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