Influence of Shield Tail Clearance on Surface Settlement during Shield Construction in Soft Soil Area

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Abstract. The shield construction process of shield tail gap caused by formation damage, the formation damage caused by the settlement is as long as the part of tunnel subsidence analysis, therefore in the finite element software analysis of shield construction settlement value, the shield tail clearance simulation is an important link in the entire model, this article analyzes three common finite element simulation method, shield tail clearance displacement convergence method based on non-uniform distribution and actual matches are higher than layer such as generation method and stiffness discount subtraction. Finally, the displacement convergence method is used to simulate the grouting effect of shield tail on the surface settlement.

Keywords. Shield tail, clearance finite element, settlement, displacement convergence method, shield tail grouting.

1. Introduction
Shield tunneling has become an advanced tunneling method in the underground engineering construction of modern cities, but shield tunneling still inevitably disturbs the stratum. Shield construction will adversely affect the surrounding buildings, and in severe cases will have disastrous consequences. At present, the main prediction methods for formation deformation caused by tunnel construction include: (1) empirical equation method, (2) analytical theory method, (3) stochastic medium theory [1], (4) finite element method, and (5) laboratory model tests. The stochastic medium theory is one of the most effective and accurate methods to predict the formation settlement caused by tunnel construction. But the calculation is complicated and cannot be widely used. The finite element method can reflect the complex constitutive relation of geotechnical materials conveniently and accurately, and has a lot of experience in engineering calculation. Because of the soft soil area shield tunnel construction risk is high. As a quantitative analysis method for risk assessment or construction prediction, numerical simulation can still obtain reasonable formation disturbance results as long as parameters are set reasonably and numerous factors such as overdigging, disturbance to the excavated surface soil, and grouting at the end of the shield, researchers are considered in the construction process of shield tunneling method.

2. Influencing Factors of Settlement of Shield Tunneling Soil
The surface subsidence caused by shield construction is mainly caused by the formation loss caused...
by excavation. Km lee et al. [2] considered that the formation deformation during shield construction is mainly affected by the following factors according to the different deformation mechanisms of soil caused by shield construction: (1) Blade disk thrust acting on the soil (2) Shield tunneling clearance (3) shield tail clearance (4) grouting pressure and synchronous grouting (5) later consolidation settlement consolidation of disturbed soil. The shield tail clearance is the main source of settlement. In order to reduce the friction resistance of the surrounding soil on the shield tunneling machine, the radius of the knife disk expansion is usually larger than the radius of the shield tunneling machine, and there will be a circular physical clearance between the shield and the surrounding soil. If the clearance around the shield is not dealt with, it will inevitably cause the formation loss, which will lead to the surface settlement and endanger the surrounding buildings. The displacement shrinkage at the top of the shield is the largest, and the displacement of the entire surrounding soil presents non-uniform convergence [3-5]. Of course, some scholars [6-7] have used the random medium theory to obtain the non-uniform convergence mode with the displacement of the stratum at the bottom of the excavated section of the tunnel not being 0. However, is a certain complexity in use, which is not discussed further in this article. At present, the commonly used simulation methods for shield tail clearance in finite element method are mainly equal ground method [8], stiffness reduction method [9], and displacement convergence [10](figure 1). The common finite element method is the equivalent layer method, which is simple to set up and easy to use, but the equivalent layer model is usually difficult to accurately calculate the shield tail clearance. In order to verify the accuracy of the three simulation methods for the shield tail clearance, the FINITE element software ABAQUS2016 was used for analysis combined with Shaoxing Subway Line 1 project, and the calculated results were compared with the field data.

![Figure 1](image-url)  
(a) Stiffness reduction method; (b) Displacement convergence; (c) Equal ground method.

3. Finite Element Simulation

3.1. Project Overview
The shield interval from The City Square to Tashan Station of Shaoxing Subway Line 1 is as follows: The shield starts from Tashan Station and finally arrives at The City Square station. Earth pressure balanced shield construction is adopted. The overburden thickness of the interval tunnel is about 9.38 m~16.603 m. The shield tunneling through the soil is mainly composed of plain filled soil, mucky clay, silty clay and clay.

3.2. Model Parameters
In this simulation, large general finite element analysis software ABAQUS was used for nonlinear analysis. In order to simplify the model, the metro line in axisymmetric mode is modeled. As shown in figure 2 the whole model is 50 m in width, 50 m in depth and 60 m in length. The soil layer, lining and grouting substitute layer adopt deformable continuous medium solid. Elastic material was used for the equivalent layers, lining and shield, and the prod step length was 1.2 m of lining ring width, a total of 50 rings. Since the effect of principal stress could not be considered by The Mohr-Coulomb model, the soil layer parameters of the D-P model were shown in Table 1. Mohr-Coulomb model to D-P model:
\[ \tan \beta = \frac{6 \sin \varphi}{3 - \sin \varphi}, \quad K = \frac{3 - \sin \varphi}{3 + \sin \varphi} \rho \frac{\sigma_\varphi^0}{\cos \varphi} = 2e \frac{\cos \varphi}{1 - \sin \varphi} \]  

(1)

Figure 2. Finite element model and soil layer parameters.

| Stratum        | E/MPa | \( \mu \) | \( \beta^\rho \) | \( d/kPa \) | \( K \) |
|----------------|-------|-----------|-----------------|-------------|--------|
| Plain fill     | 18    | 0.33      | 27.68           | 46.8        | 0.813  |
| Mucky Clay     | 10    | 0.35      | 18.27           | 30.44       | 0.901  |
| Silty Clay     | 25    | 0.32      | 32.94           | 135.14      | 0.813  |
| Clay           | 21    | 0.32      | 32.94           | 135.14      | 0.813  |
| Lining         | 30000 | 0.715     |                 |             |        |
| Shield         | 210000| 0.3       |                 |             |        |
| Grout          | 4     | 0.35      |                 |             |        |

In order to establish the values of \( E \) and at different time, the equation is as follows [11]:

\[ E_t = \begin{cases} 
E_{\text{initial}} & t = 0 \\
E_g \left[1 - e^{-\frac{t}{\tau}}\right] & t \geq t_0 
\end{cases} \]  

(2)

where, \( E_t \) is the young's modulus of grouting at time \( t \), \( E_g \) is the young's modulus after the cement slurry is completely hardened, and \( t \) is the time interval of cement slurry injection \( E_{\text{initial}} \) initial Young's modulus.

4. FEA Results and Discussions

4.1. Tunnel Surface Settlement

Due to the large surface settlement caused by shield tunneling, it is necessary to control the surface deformation within a certain range during the construction of subway. Therefore, it is particularly important to predict the soil deformation during tunnel construction. At present, the deformation caused by shield construction in China is usually predicted by Peck [12] equation.

The final surface settlement value obtained by finite element method is compared with the surface settlement value predicted by Peck equation. As shown in figure 4, it is obvious that the results of isostratified finite element analysis are consistent with Peck and empirical prediction. From figure 3 and figure 4 Comparing the surface settlement data from DBC-32-1 to DBC32-5 in the 835th ring with the results of finite element analysis, the final settlement measured by the data is 5 mm different from
the finite element calculation results, but it is still in line with the trend on the whole, which indicates that the calculated results under the equivalent layer model are too conservative. However, the stiffness reduction method and the displacement convergence method have a high consistency with the field data, especially the maximum settlement difference of the displacement convergence method is only 0.5 mm. The method of heterogeneous distribution displacement convergence is more consistent with the actual situation.

**Figure 3.** (a): Comparing surface settlements obtained from the FEA-stiffness reduction results with the field data; (b): FEA-displacement convergence results with the field data.

**Figure 4.** Comparing surface settlements obtained from the FEA-Equal ground results with the field data and the Gaussian settlement distributions.

### 4.2 Impact of the Grouting Effect on the Tail of Shield

The gap of shield tail is generally filled by grouting behind the wall. In practical projects, in order to fully fill the gap between the shield tail, the grouting amount of soft soil layer is generally between 150\% and 250\%, sometimes even higher. However, sometimes the grouting is not timely, or due to the transportation loss of slurry and problems of grouting materials, the early strength of slurry is too low, and the prolonged hardening time will lead to excessive ground settlement. In order to obtain the relationship between grouting timeliness and surface settlement, the finite element field variable method is adopted in this simulation to consider the impact of timeliness through equation (2). In order to ensure the settlement accuracy, the heterogeneous distribution mode in the displacement convergence method is adopted for simulation. It is assumed that the slurry filling rate is insufficient or the grouting is not timely. Assumed grout filling rate is insufficient or not in time the strength of grouting for 1 hour’s $E_t$, 2 hours’s $E_t$ in normal, the strength of filling rate is higher for four hours’s $E_t$.

Figure 5 shows that the grouting timeliness has a great impact on the surface. When the grouting
effectiveness is poor, the maximum settlement reaches nearly 12 mm, 2 mm larger than the normal situation. Figure 5(b) reflects the changing rule of the grouting timeliness.

![Figure 5](image.png)

**Figure 5.** (a) Surface Settlement under different time-varying conditions; (b): Relationship between maximum settlement and time.

5. **Conclusion**

In this paper, based on the ABAQUS finite element software and the shaoxing Metro Line 1 project evaluation, three different numerical models and the impact analysis of grouting timeliness on the settlement under the condition of the shield tail clearance are adopted and the following conclusions are drawn:

1. Through 3 common shield tail layer model and simulation show that gap generation under the subsidence distribution curve and gauss curve alignment, but there still exists certain gaps when compared with monitoring data, rather than the uniform mode displacement convergence method to get the settlement values in good agreement with the data on the, it also illustrates the Peck curve only can be used as a reference.

2. The impact of grouting timeliness on surface settlement cannot be ignored. Grouting should be done in a timely manner and the slurry quality should be guaranteed after the shield tail passes.

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