Deformation characteristics of latticed diaphragm wall in revetment foundation trench for one immersed tunnel

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Abstract. In this paper, based on the excavation of revetment foundation trench of an immersed tunnel project in Guangzhou, China, the influence of the insertion ratio of latticed diaphragm wall, the thickness of muddy layer under the bottom of foundation trench, the grading excavation of foundation trench and the construction of undercrossing shield tunnel are considered respectively, to study the deformation characteristics of diaphragm wall by three-dimensional numerical simulation. In addition, the finite element strength reduction method is used to analyse the stability of the latticed diaphragm wall. The results show that: the maximum lateral deformation of the latticed diaphragm wall decreases with the increase of the insertion ratio. When the insertion ratio rises to about 0.63, the lateral deformation will change slightly from then on; The increasing thickness of muddy layer has more and more influence on the lateral deformation of diaphragm wall; The deformation of diaphragm wall mainly comes from the excavation of foundation trench, and is very little affected by the excavation of the shield tunnel; Under actual working condition, the safety factor of diaphragm wall calculated by strength reduction method is about 4.1 also.

1. Introduction

In recent years, when crossing rivers and straits, immersed tunnel is more and more popular in engineering field because of its advantages of saving construction period, less tunnel length and geologic condition limit. Moreover, the excavation of foundation trench is an important part in the construction process of immersed tunnel. In this paper, the foundation trench at Fangcun end of the immersed tunnel is an ultra deep one, which is excavated by grading without support. Considering the possibility of site conditions, latticed diaphragm wall is adopted as the retaining structure of revetment, so it is very important to control the deformation and stability of the wall.

Many scholars have carried out relevant researches on the deformation characteristics of diaphragm wall: Qiao et al.[1] used the numerical simulation method to summarize the influence of the excavation depth of foundation pit, the insertion ratio of retaining wall and the position of the first support on the deformation of diaphragm wall, and obtained certain rules; Li et al.[2] summed up the deformation forms of different parts in diaphragm wall, deformation law for various characters was also researched along depth direction. Wan et al. [3] systematically studied the deformation behavior of the diaphragm wall.
during the excavation of foundation pit in Nanjing soft soil area, and obtained that the maximum lateral displacement varied from 0.05%H to 0.69%H, H represents the depth of a foundation pit.

However, the foundation trench of this immersed tunnel is deeply excavated without support, there is little research on the deformation characteristics of diaphragm wall under such condition. Based on this, this paper adopts the method of three-dimensional numerical simulation, respectively considering the insertion ratio of latticed diaphragm wall, the thickness of muddy layer, the excavation of foundation trench and new shield tunnel, analyses the influence of different factors on the lateral deformation of latticed structure. And the stability of the diaphragm wall is analysed by the strength reduction method also.

2. Engineering situation

2.1. Project introduction

The project shown in Figure 1 is a traffic corridor connecting Inner Ring Road and ring expressway. In this line, the overall length of tunnel is 1511m, and the buried section across the river adopts the immersed tube method, with a total length of 618m.

![Figure 1. General site layout of the project.](image1)

The metro line to be implemented adopts the shield method, which is very close to the immersed tunnel, with a plane clear distance of 13-50m and a vertical clear distance of 1.66-10m in the middle of the river. The longitudinal section of revetment is portrayed in Figure 2. On the basis of the geological survey data, the geological conditions in this area are very poor, the mud, muddy fine sand and sand layer are thick, and the upper layer of metro shield tunnel is thin after the excavation of foundation trench. Provided the excavation of shield tunnel is carried out before the backfilling of foundation trench, it is easy to cause revetment instability and great engineering risk.

![Figure 2. Longitudinal section of revetment.](image2)

2.2. Model overview

Z-soil finite element software is used to establish a three-dimensional numerical model for Fangcun end revetment of the immersed tunnel, as shown in Figure 3.

![Figure 3. Three-dimensional numerical model of the revetment.](image3)
The main procedures of numerical simulation are: initial geostress balance, mixing pile reinforcement, construction of diaphragm wall, excavation of foundation trench by stages and shield tunnel construction of left and right lines successively. Among them, the implementation of diaphragm wall adopts the latticed form, first, two walls are constructed inside and outside, then, adapted to the requirements in different areas, the latticed type structure is added in the middle between the two walls. Considering the differences in locations and environments, two forms of latticed structure A and B are designed, among which the A-type is divided into two forms, A1 and A2, as shown in Figure 4. A2 is used for the south side of the revetment involving shield tunnel undercrossing, and A1 is used for the north side.

![Figure 4. Different forms of latticed structure inside the diaphragm wall.](image)

### 2.3. Model parameters

HSS (Hardening Soil-Small Strain model) constitutive model is applied to this model, which can comprehensively summarize the important characteristics of soil constitutive relationship, and the physical meaning of parameters is clear, it is a high-level constitutive model suitable for soft soil [4]. According to the geological exploration report, the values of parameters in different soil layers are displayed in Table 1. C35 underwater concrete is used for walls and slabs, and elastic solid element is adopted for simulation.

| Layer number | Name                                      | \( \gamma \) | \( E_{50} \)/MPa | \( E_{90} \)/MPa | \( E_{99} \)/MPa | \( c \)/kPa | \( \phi \)/° | \( v \) | \( m \) | \( G_0 \)/MPa |
|--------------|-------------------------------------------|-------------|-------------------|-----------------|---------------|-----------|---------|------|------|-------------|
| 1            | Backfill                                  | 19          | 3.6               | 3.6             | 36            | 12        | 21      | 0.3  | 0.5  | 113         |
| 2\(_1\)      | Mud                                       | 16          | 2.1               | 2.1             | 25.7          | 13.2      | 12.3    | 0.45 | 0.8  | 63          |
| 2\(_2\)      | Muddy fine sand                           | 18.5        | 3.6               | 3.6             | 43.2          | 10        | 26      | 0.4  | 0.8  | 113         |
| 2\(_3\)      | Muddy medium sand                         | 19.5        | 4.5               | 4.5             | 45            | 10        | 28      | 0.4  | 0.8  | 143         |
| 2\(_4\)      | Coarse sand                               | 20          | 9                 | 9               | 72            | 5         | 30      | 0.3  | 0.5  | 283         |
| 3\(_2\)      | Medium and coarse sand                    | 20          | 16.2              | 16.2            | 129.6         | 5         | 30      | 0.3  | 0.5  | 269         |
| 4\(_1\)      | Silty clay                                | 19.5        | 3.6               | 3.6             | 36            | 16        | 22      | 0.3  | 0.5  | 132         |
| 5\(_2\)      | Strongly weathered argillaceous siltstone | 20          | 45                | 45              | 270           | 25        | 33      | 0.2  | 0.5  | 1249        |
| 5\(_3\)      | Moderately weathered argillaceous siltstone| 20         | 90                | 90              | 360           | 500       | 35      | 0.2  | 0.5  | 4020        |
| 5\(_4\)      | Slightly weathered argillaceous siltstone  | 20          | 135               | 135             | 540           | 600       | 42      | 0.2  | 0.5  | 8927        |
3. Influencing factors of latticed diaphragm wall deformation characteristics

3.1. Diaphragm wall insertion ratio

Different from general foundation pit with the same internal depth, the revetment foundation trench adopts sloping excavation, therefore, the depth of each part of the diaphragm wall inserted into the soil is different. In order to explore the influence of the inserting depth of the latticed diaphragm wall on its deformation characteristics, uniformly define the insertion ratio of diaphragm wall, whose value is the ratio of the depth below the bottom of the foundation ditch to the excavation depth. The insertion depths are set as 6m, 7.5m, 9m, 10.5m, 12m and 13.5m respectively, and the excavation depth is 19m, thus the corresponding insertion ratios are 0.31, 0.39, 0.47, 0.55, 0.63 and 0.71.

Arrange the lateral displacement of the diaphragm wall along the depth direction and the horizontal direction under different insertion ratios, as shown in Figure 5 and Figure 6. It can be seen from Figure 7 that the maximum lateral displacement of the ground wall decreases with the increase of the insertion ratio. When the insertion ratio is 0.31, the maximum lateral displacement of the diaphragm wall is 24.08mm, and when the insertion ratio is 0.71, the maximum lateral displacement is 12.88mm. We can come to a conclusion that when the insertion ratio decreases to a certain value, the lateral displacement of the wall will not change basically, the critical insertion ratio is about 0.63.

Figure 5. Lateral deformation of diaphragm wall along the depth direction under different insertion ratio.

Figure 6. Lateral deformation of diaphragm wall along the horizontal direction under different insertion ratio.

Figure 7. The change of maximum lateral displacement with insertion.

Figure 8. The change of maximum lateral displacement with the thickness of mud layer.
3.2. Thickness of muddy layer
By dividing the thickness of soft soil layer and taking 50%H as the demarcation line, Feng et al.[5] thought that the maximum deformation of the foundation trench with the thickness of soft soil layer ≤ 50%H was no more than 2.5‰H; The average value of the maximum deformation of the foundation trench with the thickness of soft soil layer >50%H was 3.03‰H. For exploring the influence of muddy layer thickness under the bottom of foundation trench on the lateral displacement of diaphragm wall, the thickness is set as 0m, 1.5m, 3m, 4.5m, 6m, 7.5m, 9m respectively, without changing other model parameters. Sorting out the change rule of the lateral displacement of the ground wall under the condition of different silt thickness, as shown in Figure 9 and Figure 10.

![Figure 9](image1.png)  ![Figure 10](image2.png)

Figure 9. Lateral deformation of diaphragm wall along the depth direction under different mud thickness.
Figure 10. Lateral deformation of diaphragm wall along the horizontal direction under different mud thickness.

According to the deformation characteristics of the wall along the depth direction and horizontal direction, with the thickening of muddy layer, the maximum lateral displacement of diaphragm wall will continue to increase, and the increasing amplitude will become larger and larger. As shown in Figure 8, when there is no mud distribution at the bottom of the foundation trench, the maximum lateral displacement is only 6.44mm, and when the thickness is 9.0m, the maximum lateral displacement will reach 37.98mm.

3.3. Excavation of foundation trench and shield tunnel
The foundation trench excavation of this immersed tunnel is divided into two stages, and the shield tunnel of metro line will be excavated nearby soon. In order to explore the influence of different excavation steps and the construction of left and right lines of shield tunnel on the lateral displacement of latticed diaphragm wall, three-dimensional numerical analysis is carried out.
The lateral displacement along the depth and horizontal direction under different excavation steps is shown in Figure 11 and Figure 12. It can be seen that the deformation is mainly caused by the excavation of the foundation trench. After the excavation of the first grade slope, the maximum lateral displacement value of the diaphragm wall is 9.90mm. After the excavation of the second grade slope, the maximum lateral displacement value reaches 14.50mm. However, even after the excavation of the double lines of shield tunnel, the lateral displacement of the diaphragm wall is 14.58mm, only 0.08mm increased, which is because the shield tunnel is located in the moderately weathered rock, the excavation will have little impact on the deformation of the diaphragm wall.

4. Finite element analysis of the stability of the lattice diaphragm wall

The actual working condition of the lattice diaphragm wall is: 0.55 for the insertion ratio and 4.5m for the thickness of the muddy layer. In order to prevent the instability of the lattice diaphragm wall caused by excessive lateral displacement, stability analysis is necessary. Cai et al. [6] used the strength reduction method to study the influence of the insertion depth of the retaining structure on the stability of the soft soil foundation pit; Li et al. [7] used the strength reduction method to calculate and analyze the stability coefficient of the foundation pit, and compares the difference among the calculation results when reducing different strength indexes. In this model, the strength reduction method is used to reduce the soil parameters values of cohesion force and internal friction angle, and assumed other parameters will not be affected. The reciprocal of the strength reduction coefficient of the soil parameter at the time of instability is the safety factor SF under this condition. The calculation formula is listed in Equation (1) to Equation (3), where $c$ represents cohesion force, $\varphi$ is internal friction angle and $\omega$ is the reduction coefficient.

\[
c' = \omega c \tag{1}
\]
\[
\tan \varphi' = \omega \tan \varphi \tag{2}
\]
\[
SF = 1/\omega \tag{3}
\]

When the strength reduction method is used to calculate the safety factor, there are mainly three Instability Criteria: (1) the plastic zone is through; (2) the calculation does not converge; (3) the displacement changes abruptly. Because even if the plastic zone of soil around the supporting structure runs through, the foundation pit will not necessarily lose its stability, which can only be used as a supplementary criterion [8]. Therefore, the displacement mutation and calculation non convergence are identified as the main judgment basis for the instability, so as to calculate the safety factor of the project, and take it as the reference standard for the stability evaluation of the diaphragm wall. The maximum lateral deformation of the diaphragm wall under different reduction factors is counted, and the safety factor is obtained by the intersection method [9], which is about 4.1 portrayed in Figure 13. Under this
condition, the diaphragm is in the state of instability, as shown in Figure 14, the maximum total displacement reached 80 cm.

Figure 13. The change of maximum lateral displacement with soil reduction coefficient.

Figure 14. Deformation diagram of model in case of instability and failure.

5. Conclusions

By changing the insertion ratio of latticed diaphragm wall, the thickness of muddy layer under the bottom of foundation trench, and considering the influence of two-stage slope excavation and shield tunnel excavation, the deformation characteristics of latticed diaphragm wall are studied by three-dimensional numerical simulation. At the same time, the finite element strength reduction method is employed to calculate and analyze the stability of the latticed diaphragm wall. The main conclusions are as follows:

1) The lateral displacement of the latticed diaphragm wall decreases with the increase of the insertion ratio. When the insertion ratio increases to 0.63, the lateral displacement will not change basically, thus the insertion depth of the diaphragm wall can be controlled and determined according to this, so as to achieve safe and economic effect.

2) With the increase of the thickness of muddy layer at the bottom of the foundation trench, the lateral displacement of the latticed diaphragm wall will increase, and the increasing range will become larger and larger. Therefore, in actual projects, the influence of the thickness of the muddy layer should be a major consideration.

3) The lateral displacement of lattice diaphragm wall mainly comes from the excavation of foundation ditch, and the displacement caused by the first level excavation is greater than that caused by the second level. Owning to the situation that the shield tunnel is located in the moderately weathered rock, its impact on the lateral displacement can be ignored.

4) By using the finite element strength reduction method and the intersection method, the safety factor of the latticed diaphragm wall is determined to be about 4.1, under this circumstance, the maximum lateral displacement of the diaphragm wall will reach 80 cm.

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