Deformation and Numerical Simulation Analysis of Deep Foundation Pit Excavation of Nanjing Yangtze River Floodplain Metro Station

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Abstract. Based on the foundation pit excavation construction of a subway station under the soft soil layer of the Nanjing Yangtze River floodplain, Numerical simulation of foundation pit construction process is carried out to study the deformation law of surrounding soil and surrounding structure during foundation pit construction. The research shows that the established finite element numerical model can better predict the structural and stratum deformation caused by the excavation of the foundation pit; the lateral displacement of the ground wall and the ground settlement behind the wall based on different constitutive models are different, but the overall trend is the same. The lateral displacement of the diaphragm wall presents a "bulging" pattern. The surface settlement around the pit shows a settlement trough at a certain distance from the connecting wall. The horizontal displacement of the diaphragm wall increases with the increase of the excavation depth of the foundation pit, and the maximum horizontal displacement occurs above the excavation surface. The conclusions obtained have certain guiding significance for subsequent construction and parameter optimization.

Keywords. Deep foundation pit, foundation pit deformation, constitutive model, numerical simulation.

1. Introduction

With the advancement of modernization, more and more urban construction projects in recent years, the continuous development of underground space requires complex foundation pit technology to support. Based on two deep and large foundation pits in Shanghai soft soil area, Wu C J et al. studied the influences of the shallow soft soil thickness and excavation area on the deformation of the enclosure structure and the soil around the pit [1]. Lin F et al. explored the influence of the foundation pit enclosure system on the enclosure structure and soil deformation around the pit [2-4]. Due to the complexity of foundation pit construction, foundation pit accidents occur from time to time, which has caused considerable impact on the economy and people's safety. In order to reduce the probability of foundation pit accidents, the finite element method is used to simulate the construction process of the foundation pit, and combined with the actual measurement on site, various indicators in the foundation pit construction are predicted. Wang W D et al. measured the parameters of the constitutive model used in the numerical simulation more accurately through laboratory tests, so as to make better predictions [5]. Tan Y and other
scholars monitored the deformation of the foundation pit's enclosure structure and uplift of the pit bottom, so as to controlling the impact of foundation pit excavation on existing surrounding structures [6-7].

Based on a subway station project on the Yangtze River floodplain in Nanjing, this paper comprehensively uses on-site monitoring and numerical simulation methods to conduct a systematic study on the lateral displacement of the ground wall and the ground settlement behind the wall caused by the construction of soft soil foundation pits to guide Subsequent construction of similar projects.

2. Project Overview
Mochou Lake Station is located on the banks of the Qinhuai River in Jianye District, Nanjing. It is interchangeable with Mochou Lake Station on Line 2. The excavation depth of the foundation pit is 34 m. The station has 5 entrances and exits, of which 3 are passenger entrances and exits (2 are emergency evacuation safety exits), and there are 2 fire evacuation exits. The main structure of the station is a double-column three-span box frame with a column spacing of 9 meters. The total length of the station structure is 160.00 m, the total width of the standard section structure is 22.15 m, and the roof covering thickness is about 2.50 m.

For soft soil foundation, the enclosure structure of deep earth diaphragm wall + support is adopted to form a stable and reliable enclosure structure of "underground foundation pit", which can withstand the large lateral soil pressure caused by the excavation of large and deep foundation pit and reduce the vertical settlement of soil outside the pit. The superstructure works smoothly, the working site is relatively wide, the excavation and construction are convenient, and the construction speed is fast. When the substructure is reversed, the floor acts as a part of support, which reduces the lateral deformation of soil. The construction method combined with positive and negative factors has obvious effect considering the double influence of time limit and soil settlement. The reinforcement of the pit bottom can reduce the displacement of the maintenance structure during the excavation stage and improve the soil resistance of the ground floor of the station.

2.1. Overview of Foundation Pit
The depth of the station foundation pit is about 34 m and the width is about 21.9 m. The top-down construction method is adopted for the open-cut and smooth construction + underground two-story and three-story underground floor frame. Enclosure structure adopts 1200 mm thick underground continuous wall, which is constructed by slot milling machine, and the wall length is 64.0 m. Six supports are arranged within the depth of the foundation pit, Nine supports are arranged in the depth of the foundation pit. The first, fifth and sixth are reinforced concrete supports, and the second, third and fourth are Φ609 steel supports. Figure 1 shows the plan view of the foundation pit (the foundation pit is the yellow area).

Figure 1. Plan of foundation pit.
2.2. Hydrogeology
The geology of the soil layer of the project site is relatively complex, and table 1 shows the soil quality and depth.

| Table 1. Modified Mohr Coulomb parameters. |
|--------------------------------------------|
| Miscellaneous fill | Silty clay | Silt with silt | Silty clay | Silt | Silty clay with silt | Silt | Weathered rock |
|---------------------|-----------|----------------|-----------|------|---------------------|------|----------------|
| Poisson's ratio     | 0.34      | 0.32           | 0.28      | 0.3  | 0.29                | 0.33 | 0.31           | 0.26 |
| Bulk density/kN/m³   | 18.7      | 17.9           | 18.8      | 18   | 18.8                | 19   | 19             | 22.9 |
| Permeability/e-6cm/s | 100       | 5              | 500       | 50   | 3000                | 200  | 20000          | 10   |
| k₀                  | 0.74      | 0.39           | 0.53      | 0.3  | 0.36                | 0.33 | 0.3            | 10   |
| Initial void ratio e₀ | 0.938  | 1.134          | 0.834     | 1.072 | 0.864               | 1.012 | 0.762         |
| Unloading modulus of elasticity/kPa        | 18900     | 16950          | 41000     | 22300 | 42950               | 25250 | 49750         | 42500 |
| Friction angle at shear failure            | 14.75     | 14.21          | 26.71     | 20.2 | 28.71               | 21.36 | 31.57         | 48   |
| Cohesion/kPa                                   | 20.54     | 13.07          | 8.03      | 14.15 | 7.66                | 11.41 | 7.13         | 5    |
| Thickness /m                    | 4         | 7              | 4         | 4    | 4                   | 4     | 4              | 8    |

During the survey, the buried depth of the site was measured by diving. According to the measurement results, the groundwater depth of the site was 0.70-2.50 m and the average elevation was 5.39 m; the stable water level was 0.90-2.30 m and the average elevation was 5.49 m. According to the investigation, the groundwater of the proposed site is mainly stored in the fill and the newly deposited soil. The annual water level changes by 1 to 2 m, and the highest groundwater level in the history of the site is close to the surface.

2.3. Monitoring Plan
This paper mainly studies the horizontal displacement of underground diaphragm wall and the variation law of soil settlement around the pit under different construction conditions. Figure 2 shows the layout of monitoring points around the foundation pit.

![Figure 2. Layout of monitoring points on ground wall.](image-url)
3. Establishment of Numerical Model of Foundation Pit Excavation

3.1. Finite Element Software and Material Constitutive Model
In this paper, the general-purpose large-scale geotechnical engineering finite element software Gts nx is used for modeling, and the constitutive model of soil mass is calculated by modified Mohr Coulomb, modified Cambridge model, and Guankou-Ota model, and compared. Modified Mohr Coulomb can consider the compression hardening and shear hardening of the soil, which can better simulate the unloading effect of the soil; the modified Cambridge model is often used for normally consolidated or weakly consolidated clays; the modified gateway-Ota model and the modified Cambridge model. The parameters are the same, but the yield trajectories of the two are different. Due to space limitations, only the modified molar coulomb parameters are explained now. The modified molar coulomb parameters are shown in table 1.

3.2. Model establishment
The influence range of foundation pit excavation is 3~5 times of the excavation depth in the horizontal direction, and 2~4 times of the excavation depth in the vertical direction. The excavation depth of the foundation pit of this project is 33 m, of which the length of the right-angle side in the north-south direction is 158 m, and the length of the right-angle side in the east-west direction is 26 m, which is a long and narrow deep foundation pit. Combined with the scope of influence, a three-dimensional model of model length×width×height=360 m×230 m×100 m is established. Figure 3 shows the three-dimensional model of the foundation pit.

![Figure 3. Foundation pit model.](image)

3.3. Excavation Steps
The excavation steps should not only conform to the construction, but also not that too many steps will cause the calculation to be too slow, and certain simplifications were made in the modeling. Due to space constraints, the excavation steps are only written down to the second floor, but the comparison of the results later is based on the completion of the fourth floor. Table 2 shows the detailed process of foundation pit excavation.
Table 2. Excavation steps of foundation pit.

| Step | Construction content |
|------|-----------------------|
| 1    | Construction support 1 |
| 2    | Construction support 2 + Excavation of soil layer 0-7m |
| 3    | Construction support 3 + Excavation of soil layer 7-11m |
| 4    | Construction support 4 + the bottom plate of negative second floor + Excavation of soil layer 11-17m |
| 5    | Remove the support 3/4 + Roof of negative second floor |
| 6    | Remove the support 2 + Roof of negative first floor |

4. Analysis of Actual Measurement Results and Finite Element Calculation Results

For comparison, we select the 7-7 cross-sections with monitoring points for analysis, and the location is at the connecting line of the horizontal displacement monitoring points ZQT10 and ZQT11 of the ground wall (see figure 2 for the location).

4.1. Horizontal Displacement of Diaphragm Wall with Different Constitutive Models

Figure 4 shows the comparison between the measured value and the numerical simulation result of the horizontal displacement monitoring point ZQT10 of the underground diaphragm wall (the location of the monitoring point is shown in figure 2).

![Figure 4. Lateral displacement of diaphragm wall of different constitutive models.](image)

From the comparison of the numerical calculation results of the two constitutive models and the monitored values in Fig. 4, it can be seen that: (1) From the perspective of the variation of the lateral deformation of the diaphragm wall with depth, the numerical calculations and measured values under the
two constitutive models. The upper and lower ends are small in the middle and the middle is large, and the lateral displacement at the top and bottom of the ground connecting wall is close to 0, which indicates that the rigidity of the first layer of support and purlin is sufficient, which limits the top of the ground connecting wall. The displacement also shows that the embedded depth of the ground connecting wall is sufficient, which effectively limits the displacement of the bottom of the wall. (2) As the excavation depth of foundation pit increases, the horizontal displacement of the diaphragm wall also increases, and the maximum horizontal displacement of the partition wall is always above the excavation surface. With the excavation and unloading of the soil in the pit, the earth pressure of the soil outside the pit on the diaphragm wall gradually increases, which causes the lateral displacement of the diaphragm wall to increase continuously. (3) Among the two constitutive models, the MCC model is the closest to the measured value trend, which also shows that in soft soil areas, using this constitutive model can better simulate the real situation.

It can be seen from the above analysis that the numerical model established in this paper can predict the deformation of the retaining structure during the excavation of foundation pits and provide guidance for subsequent construction.

4.2. Surface Settlement around the Pits of Different Constitutive Models

The surface settlement around the pits of different constitutive models is shown in Figure 5.

![Figure 5. Surface settlement behind the wall of different constitutive models.](image)

It can be seen from figure 5 that the two constitutive models and the monitoring values of the surface settlement of the soil around the pit all have settlement troughs at a certain distance from the ground connecting wall, but the positions of the settlement troughs are slightly different. The MCC model is different from. The monitoring value fits most closely. At the same time, it can be seen that as the distance increases, the settlement of the soil around the pit increases first and then decreases to 0, which also shows that the influence range of foundation pit excavation in the horizontal direction is 3 to 5 times of the excavation depth.
5. Conclusion
In this paper, two methods of on-site measurement and numerical simulation are used to study the deformation characteristics of the deep foundation pit retaining structure and surrounding stratum of Nanjing Yangtze River Floodplain Metro Station, and the following conclusions are drawn:

The three-dimensional model in this paper can predict the lateral deformation of the support structure during excavation. As the excavation depth of foundation pit increases, the horizontal displacement of the diaphragm wall also increases, and the maximum horizontal displacement of the partition wall is always above the excavation surface. Among the two constitutive models, the MCC model is in good agreement with the monitored values.

The three-dimensional finite element model established in this paper can predict the deformation of the surrounding ground during the excavation of foundation pits. A settlement trough appears at a certain distance from the ground connecting wall. As the distance increases, the impact of foundation pit excavation gradually decreases and eventually dissipates.

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