Numerical Analysis of Deep Foundation Pit Excavation Process

Xiaoyi Jiang¹, Qingrui Lu²*, Xiaopeng Chen¹, Jinling Liu¹ and Ping Li¹

¹ School of Civil and Architectural Engineering, East China University of Technology, Nanchang, Jiangxi Province, 330013, China
² State Key Laboratory of Nuclear Resources and Environment (East China University of Technology), Nanchang, Jiangxi, 330013, China
Email: ecutjiang@163.com

Abstract. Based on the background of a subway project to be built in a certain city, finite element analysis software Abaqus 6.1.4 was used to simulate and analyze the displacement changes of deep foundation pit excavation, underground diaphragm wall, steel support and other supporting structures. The results show that the maximum horizontal displacement of the diaphragm wall and the vertical displacement (settlement) of soil around the foundation pit occur at the midpoint of the long side of the foundation pit. The maximum horizontal displacement of the underground diaphragm wall reaches 13.9 mm, and the maximum horizontal displacement occurs 16m from the top of the wall. The maximum vertical displacement (settlement) of soil around the foundation pit is 9.5 mm and occurs 8m away from the edge of the foundation pit. For the deep foundation pit with large length and width, the deformation of the middle point and the end section of the long side of the underground diaphragm wall is relatively large compared with other positions, so a reasonable alarm value should be set separately. The axial force of steel support on the excavation layer will increase significantly, which is a focus of close attention in design and construction. The above results can provide some reference for the design and research of deep foundation pit excavation support in soft soil area.

Keywords. Subway deep foundation pit, finite element method, horizontal displacement, soil settlement, strut axial forces.

1. Introduction
At present, it is difficult for overground space to meet the rapidly growing land demand in China's urbanization process, and the development and utilization of underground space have been increasingly emphasized in the engineering field. Major cities in central and eastern China have large population density but limited overground space, so the rational development of urban underground space has become extremely urgent [1-5]. To cope with the above problems, a number of subway lines have been opened in some developed cities in China. By October 2020, 20 subway lines have been opened in Shanghai alone. The extension project of Subway Line 17 to Jiaxing will be started in 2021, and the subway foundation pit project will gradually develop to the direction of super deep and super large. Subway projects are generally located in the center of the city, and most of the foundation pit excavation is also located in the place with high density of urban buildings. Most of the foundation pits cannot meet the conditions of slope excavation, so deep foundation pit excavation should be adopted. Therefore, in the process of deep foundation pit excavation, horizontal displacement of...
underground diaphragm wall, settlement of surrounding soil and axial force monitoring of steel support have become a hot issue in underground space engineering in recent 5 years. The boundary conditions of deep foundation pit construction are too complex, and it is generally difficult to solve the deformation of foundation pit support structure and settlement of surrounding soil by analytical method in the construction process. Numerical analysis provides a favorable solution [6-9].

Literature [10-14] has studied and analyzed the measured results of deep foundation pit in urban construction in China in recent ten years, obtained the deformation law of deep foundation pit enclosure structure and the law of surrounding surface settlement, and found that the location of large deformation of foundation pit with large length and width is generally in the middle point of the long side of foundation pit and the end of standard section. Zhu Yanpeng et al. [15] analyzed and simulated the field monitoring data and found that when the foundation pit began to be excavated, the pile top had a large horizontal displacement and presented a forward distribution along the pile body. As the foundation pit is gradually excavated downwards, the part with large displacement is moved downwards. After the steel tube is supported, the horizontal displacement curve of bollards is arched, and the maximum value is about 1/2-1/3 of the pit depth. After analyzing and simulating the monitoring data of deep foundation pit in a subway station, Huo Runke et al. [16] found that the axial force of steel support increased rapidly in the initial stage of foundation pit excavation, and the axial force was also nearly stable as the excavation was nearly completed. Compared with the concrete support, the axial force of the steel support will show a quadratic curve increase at the beginning of excavation, and it will start to level off when it reaches a certain value.

In this paper, Abaqus 6.1.4 finite element analysis software is used to simulate the deformation and displacement of each supporting structure and surrounding soil during the excavation and support of foundation pit against the background of a subway project to be constructed in a certain city, aiming to provide theoretical reference for the design of large and deep foundation pits in soft soil areas.

2. Project Overview

2.1. The Foundation Pit

The station foundation pit is 208.9 m long, 19.7 m wide in standard section and 16.88-17.3 m deep. The broadened section of shield shaft is 26.3 m wide and 18.3-18.7 m deep. Hill station using underground continuous wall, concrete support and steel support form of palisade, underground continuous wall thickness 800 mm, the entire construction process support top-down set 5, the C30 concrete supporting in the first level, cross section size is 800 mm * 700 mm, 2-5 layer using Φ 609 mm x 16 mm steel support, end four Angle of the inclined support of foundation pit. The retaining structure section of the standard section of the foundation pit is shown in figure 1. The concrete support is 9 m apart in the standard section and 7.5 m apart in the non-standard section. The 2-5 layers of steel support are uniformly laid out.

Figure 1. Section diagram of retaining structure in standard section of foundation pit (mm).
2.2. Engineering Geological Conditions

The underlying soil layer in the foundation pit area is as follows: gravel filling; muddy clay; silty clay; completely weathered tuff. Silt clay and silty clay are the main soils exposed during the excavation of foundation pit. According to laboratory test results and exploration experience, silty clay contains a small amount of organic matter and humus, which is smelly, and the local phase turns into silt. It is a high-compressibility soil, and a small amount of silty thin layer is included in the local pore section. Silty clay is soft and plastic, containing a small amount of iron and manganese nodules and rust spots.

According to the geological survey report and field laboratory tests, relevant parameters of each soil layer are obtained, as shown in Table 1.

| Serial number | Name of the soil       | Bottom elevation /m | γ′ / (kN·m⁻³) | ω/ % | Es1-2 /MPa | c /kPa | φ(°) | μ | E /MPa | f |
|---------------|-----------------------|---------------------|---------------|------|------------|-------|------|---|--------|---|
| (1)           | Gravel filling        | -2                  | 18.6          | 31.4 | 4.0        | 3     | 10   | 0.2| 31     | 0.22 |
| (2)           | Mucky clay            | -6                  | 17.2          | 47.4 | 3.5        | 13    | 9    | 0.3| 20     | 0.21 |
| (3)           | Silty clay            | -24                 | 19.3          | 26.8 | 6.0        | 46    | 17   | 0.3| 35     | 0.32 |
| (4)           | Fully weathered tuff  | -60                 | 23.0          | /    | /          | 200   | 34   | 0.2| 240    | 0.55 |

Note: γ′ for soil heavy; ω for the natural moisture content of soil; Es1-2 is the compression modulus of soil mass; c is the cohesion of soil mass; φ refers to the internal friction Angle of soil; μ is poisson's ratio of soil mass; E is the elastic modulus of soil; f is the friction coefficient of the contact surface.

3. Finite Element Analysis

3.1. Numerical Modeling Approach

A three-dimensional 1:1 finite element model with a size of 350m×150m×60m was established. Solid unit modeling is adopted for soil mass and underground diaphragm wall. The support is modeled by the beam element. The solid element mesh type is C3D8R six-node solid element, and the support is B31 beam element. While ensuring the accuracy, the elements near the underground continuous wall are encrypted, and the number of grids in the distance is reduced to speed up the calculation. The contact type between soil and wall is contact model, tangential is penalty function and normal is hard contact. In the process of creating contact surfaces, contact surfaces are created according to different soil layers. The two surfaces of the wall are the main surfaces facing the internal and external contact, and the surfaces of the soil inside the wall and the external soil are slave surfaces [17]. The binding contact is selected between the underground diaphragm wall and the supporting system. Since there are no other projects or large buildings around the foundation pit, the surface traffic load is mainly considered in the calculation.

3.2. Calculation Parameters

The more-Coulomb ideal elastic-plastic model is adopted in the whole model. The underground diaphragm wall and its support are elastic models with elastic modulus of 30 GPa and 209 GPa respectively, and the support is beam unit. The soil layer parameters after partition are shown in Table 1.

3.3. Calculation Steps

The simulation calculation process is designed according to the specific construction conditions, and the important steps are: A. Equilibrium initial geostress field; B. Excavate 1-5 layers of soil and install 2-5 layers of steel support, among which the soil layers excavated 1-5 layers are divided into a layer of 3 meters thick.
3.4. Calculation Results

3.4.1. Horizontal Displacement of Ground Connecting Wall. Figures 2 (a) and (b) respectively represent the horizontal displacement cloud maps of the underground diaphragm wall after the excavation of the first soil layer and the fifth soil layer. In the figure, U2 represents the horizontal (Y-axis) displacement of the ground diaphragm wall. From the first working condition in figure 2 (a) to the last working condition in figure 2 (b), it can be seen that the maximum horizontal displacement of the underground diaphragm wall gradually moves down. Figure 3 shows the changes of the horizontal displacement of the wall at the mid-point section of the underground diaphragm wall and at the end section of the standard section after each excavation and erection of support. According to the construction sequence, there are altogether 9 working conditions. Working condition 1 is the excavation of the first soil layer, working condition 2 is the erection of the first steel support, and so on in the following 7 working conditions. After the excavation of the last soil layer, no steel support is erected. As shown in figure 3, from working conditions 1-9, the maximum horizontal displacement of the underground diaphragm wall occurs within the midpoint range of the long side of the foundation pit. With the gradual increase of the excavation depth of the foundation pit, the maximum horizontal displacement also increases gradually, and the maximum horizontal displacement occurs at the same time gradually moves down. It can be seen from the figure that when the excavation is completed, the maximum horizontal displacement at the midpoint is 13.9 mm, and the maximum horizontal displacement at the end is 11.07 mm. The maximum horizontal displacement occurs at 16 m and 12.8 m away from the top of the wall respectively. The main reason for this result is that the midpoint position of the long side bears the maximum bending moment.

![Horizontal displacement cloud map of underground diaphragm wall.](image1)

(a) End the excavation of the ground floor  
(b) End the excavation of layer 5

Figure 2. Horizontal displacement cloud map of underground diaphragm wall.

![Horizontal displacement of underground diaphragm wall under various operating conditions.](image2)

A. Long midpoint  
B. End of standard segment

Figure 3. Horizontal displacement of underground diaphragm wall under various operating conditions.

3.4.2. Soil Settlement around Foundation Pit. Figure 4 is the relation diagram of soil settlement and foundation pit distance at the midpoint and end of long side of foundation pit under various working conditions. It can be seen from the figure that the position of maximum settlement around the whole foundation pit is at the midpoint of the long side of the foundation pit, and gradually decreases towards
both ends. With the increase of the excavation depth of the foundation pit, the influence range of the settlement generated on the soil around the foundation pit gradually increases. Until the end of excavation, the maximum settlement at the middle point of the long side of the foundation pit and the maximum settlement at the end of the standard section is 9.5 mm and 5.8 mm, both of which occur at 8 m away from the edge of the foundation pit. The influence range of surrounding soil settlement is about 40 m, and the main influence range is about 20 m.

![Figure 4](image-url)

Figure 4. Soil settlement around foundation pit under various conditions.

3.4.3. Supporting Axial Force. The calculation results show that the peak of axial force of each support layer and each working condition occurs after excavation. When the excavation of the 5th floor is completed, the peak of axial force of the 4th floor and the 1st floor are the largest, followed by the peaks of the 2nd and 3rd floors.

4. Conclusion

In this paper, based on Abaqus 6.1.4, a finite element model was established by using numerical simulation analysis method to study the deformation rule of deep foundation pit excavation envelope, and the following conclusions were drawn:

1) In the process of foundation pit excavation, when soil mass uses the Mohr-Coulomb model, it is found that the maximum horizontal displacement position of underground diaphragm wall is at the middle point of the long side of the foundation pit, and then the excavation depth increases, and the position gradually moves downward until the excavation ends and the position is at the depth of foundation pit 0.6H.

2) There is a certain degree of difference between the calculated value of soil settlement around the foundation pit and the field measured value in similar literature, mainly due to the limitations of the numerical model and the differences between the simulated environment and the field construction to a certain degree.

3) For deep foundation pit with large depth, length and width, the deformation of underground diaphragm wall at the middle point and the end of the long side section is greater than that at other positions. Therefore, these two positions should be considered separately in engineering design and a reasonable alarm value should be set. Secondly, in the field monitoring, if the section has construction behavior, it is necessary to carry out encryption monitoring to ensure the safety of the site construction.

4) As for the change of the axial force of the steel support, the calculated data show that during the excavation of the foundation pit, the axial force of the upper layer of the steel support will increase significantly. Therefore, the influence of this sudden change on the safety reserve of steel support should be considered in the design, and the change of axial force of steel support should be paid close attention during the on-site monitoring process.
Acknowledgements
This research was sponsored by the following items: The State Key Laboratory of Nuclear Resources and Environment(East China University of Technology)(NRE1930); The graduate innovation fund of East China University of Technology(YC2020-S499); The Natural Science Foundation of Jiangxi, China (Grant No. 20202BABL204055); The National Natural Science Foundation of China(Grant No. 41672278).

References
[1] Jiang X F, Liu G B, Zhang W L and Li X Y 2010 Study on deformation characteristics of Ultra-deep Foundation Pits in Shanghai based on measured data Journal of Geotechnical Engineering 32(S2) 570-573.
[2] Liu B C 1999 Several problems of comprehensive utilization of urban surface and underground space Journal of Rock Mechanics and Engineering (01) 3-5.
[3] Li X Z, Li C C, Aurèle P, Wu W, Li H Q, Sun L P and Liu C 2016 Multiple resources and their sustainable development in Urban Underground Space Tunnelling and Underground Space Technology 55 59-66.
[4] Chen Z L, Chen J Y, Liu H and Zhang Z F 2018 Present status and development trends of underground space in Chinese cities: Evaluation and analysis Tunnelling and Underground Space Technology 71 253-270.
[5] Q Q H 2016 Present state, problems and development trends of urban underground space in China Tunnelling and Underground Space Technology 55 280-289.
[6] Ye S H, Ding S H, Gong X N, Gao S and Chen C L 2018 Monitoring and numerical simulation analysis of deep foundation pit in a subway station in Lanzhou Journal of Geotechnical Engineering 40(S1) 177-182.
[7] Xie W, Lu K L and Zhu D Y 2017 Monitoring and numerical simulation of subdivision excavation of deep foundation pits in subway Journal of Changjiang Academy of Sciences 34(12) 106-110+121.
[8] Zhang D M, Xie X C, Li Z L and Zhang J 2020 Simplified analysis method for predicting the influence of deep excavation on existing tunnels Computers and Geotechnics 21.
[9] Zhang M J, Xie Z T and Li P F 2020 Experimental and numerical investigation on the bearing capacity of disconnectable coupling (DC) joints for prestressed internal bracing in subway excavations Tunnelling and Underground Space Technology Incorporating Trenchless Technology Research 04.
[10] Jin G Z 2018 Deformation monitoring and analysis of deep foundation pit construction in soft soil railway station Railway Construction Technology (12) 81-85+92.
[11] Wei G, Hua X X and Yu X F 2016 Monitoring and analysis of deep foundation pit excavation construction of a subway station in Hangzhou Journal of Wuhan University (Engineering Science edition) 49(06) 917-923+936. (in Chinese)
[12] Gu M N, Zhuang H Y, Liu X C, Wu X Z and Feng S S 2015 Statistical Analysis on deformation law of foundation pit of subway station in deep and weak site Journal of Underground Space and Engineering 11(S1) 172-176.
[13] Yu J L, Xia X, Zhang W and Hu L 2014 Analysis of the influence of sand soil Foundation Pit engineering on the Surrounding environment Journal of Geotechnical Engineering 36(S2) 311-318.
[14] Wu J G, Wang Y X and Yang Y H 2013 Monitoring and analysis of shaft force of steel support for deep foundation pit of Hangzhou Metro Station on Qiutao Road Railway Construction (10) 51-54.
[15] Zhu Y P, Yang X H, Zhou Y and Ran G 2016 Support type selection analysis and numerical simulation research of deep foundation pit in Lanzhou Metro Station Journal of Shui Li and Construction Engineering 14(01) 55-59.
[16] Huo R, Yan M Y and Song D 2011 Monitoring and numerical analysis of deep foundation pit
excavation of subway station Journal of Railway Engineering 28(05) 81-85.
[17] Xu J, Gong W, Mu B G, Liu B, Zhang Q and Dai G L 2017 Numerical simulation and field monitoring of deep foundation pit construction process of a subway in soft soil area Journal of Southeast University (Natural Science Edition) 47(03) 590-598.