Numerical Analysis of Deep Foundation Pit Excavation under Complex Beam Support

Changyi Yu$^{1,2,3,4}$

$^1$ CCCC-Tianjin Port Engineering Institute, Ltd., Tianjin 300222, China
$^2$ CCCC First Harbor Engineering Company, Ltd., Tianjin 300461, China
$^3$ Key Laboratory of Geotechnical Engineering, Ministry of Communications, Tianjin 300222, China
$^4$ Key Laboratory of Geotechnical Engineering of Tianjin, Tianjin 300222, China;

* Corresponding author’s e-mail: yu_longone@163.com

Abstract. With the deepening of people's understanding of foundation pit engineering, people pay more and more attention to the three-dimensional characteristics of foundation pit engineering, and the continuous development of computer technology makes it possible to carry out complex three-dimensional finite element analysis of foundation pit. The three-dimensional space finite element of foundation pit is a whole structure that regards all supporting systems and vertical retaining structures as a coordinated work, which can simulate various construction conditions and calculate the internal force and deformation of each component under each working condition. This whole calculation method can also take into account the influence of the deformation of the previous working condition through the life and death technique of the unit, so that the calculation model is basically consistent with the actual situation.

1. Introduction

The excavation area and depth of foundation pit are constantly increasing, which makes the foundation pit project show strong complexity and uniqueness. First of all, different foundation pits have different engineering geological conditions and hydrogeological conditions, and the supporting scheme and excavation scheme need to be adapted to local conditions, so the existing engineering experience cannot be simply copied[1]. Especially in some areas with special geological conditions, such as Shanghai, Haikou and other cities, the geological conditions are poor and the foundation deformation is serious, making the deformation control of deep foundation pit a big difficulty. Secondly, the higher the urbanization, the more complex the adjacent buildings in the city, such as the adjacent high-rise buildings, viaducts, subway stations, underground pipe networks, etc., the underground water level and stress field will be redistributed during the foundation pit construction process. Therefore, it is necessary to consider not only the impact of adjacent facilities on the safety of the foundation pit, but also the impact of foundation pit construction on the safe use of the surrounding sites[2-3].

Liu[4] made statistics on the measured data of more than 60 foundation pit projects in order to study the interaction between the retaining structure, supporting methods and soil of the foundation pit, and obtained the influence of wall types and supporting methods on the deformation of the foundation pit under different soil conditions. The statistical results show that the wall types and supporting
methods in gravel or hard clay have little influence on the deformation of foundation pit. On the soft clay foundation, the underground continuous wall has better supporting effect than the flexible structure. Wang with his co-workers[5] combined with the data of 11 hard clay foundation pits with flexible supporting structures, considered that there was a certain relationship between the lateral displacement of the foundation pit supporting structures and the uplift resistance coefficient of the pit bottom, and proposed a method to estimate the maximum ground settlement based on the uplift resistance stability coefficient of the pit bottom. Finno with his cooperators[6] carried out research on medium-hard clay foundation pit, and obtained the relationship between the uplift resistance coefficient of the pit bottom, the support stiffness of the foundation pit and the maximum lateral displacement of the retaining structure, and also studied the maximum lateral displacement of the foundation pit and the excavation depth of the foundation pit under geological conditions such as hard clay, sand and so on.

In this paper, the construction process of a deep foundation pit is simulated by finite element method, and a large-diameter ring beam supporting system model is established by nonlinear finite element method. The advantage of this model is that the soil mass, the wall of the ground connecting wall and the supporting system are analysed and calculated as a unified whole, which can avoid the defect of uncoordinated deformation among various components in the previous calculation and the deformation results obtained by the calculation are more in line with the actual situation.

2. Numerical model

In principle, the boundary range of the calculation model should reach the boundary where no deformation or internal force will occur after the foundation pit excavation structure is stressed. However, due to the limitation of calculation conditions, calculation resources and time, it often cannot meet the requirements completely consistent with the actual situation. Generally speaking, the stress and deformation of soil beyond 3 times the actual size of foundation pit can be ignored. Therefore, the length, width and depth of the foundation of FEM model are about 675 m, 510 m and 68 m respectively.

In this project, the ground connecting wall is set around the foundation pit. In the process of establishing the model, a continuous wall with consistent stiffness is established for analysis and calculation. When modelling, the wall depth is 35m and the thickness is 1m. According to the data, five supports were set up in the process of foundation pit excavation, and the form and size of the supports were given according to the design drawings.

Figure 1 shows the finite element model of the soil within the calculation range, figure 2 shows the finite element model of the diaphragm wall, and figure 3 shows the finite element model of the support. The Y axis direction is the depth direction of foundation pit excavation.

In order to calculate quickly, the soil grids inside the foundation pit and around the ground connecting wall are finely divided. With the increase of distance from the foundation pit edge, the grid division is relatively sparse. The element type is a spatial 8 - node hexahedron element. Because it is a three-dimensional stress analysis, the mesh type adopts a three-dimensional stress analysis.

![Figure 1. Soil model mesh.](image1)

![Figure 2. Diaphragm wall model.](image2)
In general foundation pit engineering, the contact involved is wall-soil, wall-support. In numerical simulations, it can be assumed that there is no slip between the enclosure and the horizontal support system. However, the outer side of the envelope structure is in contact with the soil to cause relative sliding. The soil needs to be large enough to ensure that the boundary does not affect the settlement outside the pit.

Table 1. Calculation parameters of soil layer selected by finite element method.

| Solum                  | Thickness (m) | Severe (kN/m³) | φ(°) | c(kPa) | Elastic modulus (MPa) | Poisson's ratio |
|------------------------|---------------|----------------|------|--------|-----------------------|-----------------|
| Miscellaneous fill     | 1.5           | 18.5           | 5    | 5      | 6                     | 0.25            |
| plain fill             | 3.5           | 19.4           | 10.48| 13.63  | 8                     | 0.25            |
| Silty clay mixed with  | 3.5           | 18.9           | 18.3 | 12.8   | 16                    | 0.3             |
| silt                   |               |                |      |        |                       |                 |
| Silty clay             | 8.5           | 17.9           | 6.87 | 9.29   | 3                     | 0.3             |
| Silty clay             | 8.5           | 17.9           | 6.87 | 9.29   | 3                     | 0.3             |
| Clay                   | 2.5           | 19.2           | 14.89| 17.59  | 13                    | 0.3             |
| Silty clay             | 3             | 20.2           | 17.19| 14.76  | 12                    | 0.3             |
| Silty clay             | 2             | 20.6           | 25.2 | 9.4    | 18                    | 0.3             |
| Silty clay             | 2.5           | 19.8           | 18.45| 16.9   | 15                    | 0.3             |
| Silty soil             | 2.5           | 20.8           | 28.47| 9.92   | 19                    | 0.3             |
| Silty soil             | 2.5           | 20.8           | 28.47| 9.92   | 19                    | 0.3             |
| Silt                   | 23            | 20.4           | 30.74| 0      | 24                    | 0.3             |

The envelope structure and horizontal support system are approximately C30 concrete material, assuming elastic deformation.

The calculation of the model is carried out in three steps. The first step is to calculate the initial stress field before foundation pit excavation. Since the soil has experienced long-term consolidation in history and has reached a stable state, the displacement field in the first step of calculation is zero. The
second step is to calculate the displacement field caused by the first step of foundation pit excavation. The third step is to calculate the displacement field after the horizontal support is applied and the second step of excavation of the foundation pit.

3. Calculation result

Due to the excavation of the foundation pit, the inherent balance state of the soil body is destroyed, and the soil body at the bottom of the foundation pit rebounds upward and bulges. At the same time, due to the lateral unloading of the soil body, the supporting wall body moves towards the foundation pit, and the soil body behind the wall moves, causing the surface settlement. Therefore, the deformation of foundation pit excavation mainly includes three parts: wall deformation, surface settlement behind the wall, and uplift at the bottom of the foundation pit.

The most direct consequence of foundation pit excavation unloading is to break the initial equilibrium state of the soil mass, causing the redistribution of the stress of the soil mass around the foundation pit, thus causing the movement and deformation of the surrounding strata, resulting in ground settlement and uneven settlement, and the deformation of the soil mass toward the inside of the foundation pit, adversely affecting the surrounding environment. In order to protect the safety of the surrounding environment of foundation pit, the current design code of foundation pit puts forward the calculation method of deformation and stress of foundation pit retaining structure, but there is no analysis method of additional deformation of foundation pit excavation. Research shows that the influence of foundation pit excavation on the surrounding environment has obvious zoning characteristics, and it is generally believed that the main influence range of ground settlement caused by foundation pit excavation is twice the depth of foundation pit excavation. The horizontal displacement of stratum is often the main cause of structural damage to the underground structure outside the pit, but the current study on the displacement field outside the pit is not deep enough.

Surface subsidence is due to excavation of foundation pit and strata movement, which appears in the vertical deformation form of the ground around the foundation pit. Foundation pit excavation is the process of unloading the soil on the excavation surface at the bottom of the foundation pit. After unloading, the soil at the bottom of the pit rebounds and produces upward displacement. At the same time, the earth pressure on both sides of the diaphragm wall varies, and the earth outside the foundation pit will move horizontally inward under the influence of the earth pressure difference.

The rebound of the soil under the pit is caused by the self-weight stress of the soil being removed during the excavation of the foundation pit and the insufficient depth of wall insertion, and the soil outside the pit moves from the bottom to the inside of the pit, resulting in the uplift of the pit bottom. After unloading, the soil mass at the bottom of the pit bulges vertically, with the amount of uplift at the bottom of the pit being large in the middle and small on both sides.
From the above calculation results of soil deformation, it can be seen that after the excavation of the foundation pit, the surrounding soil has significantly settled, and the maximum settlement is located in the middle of the contact between the diaphragm wall and the soil outside the pit. The bottom of the foundation pit is uplifted, and the maximum uplift amount is approximately in the middle of the pit bottom.

When the foundation pit is excavated, the original earth pressure is removed from the inner side of the diaphragm wall, while the outer side of the foundation pit is subjected to active earth pressure, while the inner side of the diaphragm wall is subjected to all or part of passive earth pressure, resulting in deformation and displacement of the diaphragm wall due to unbalanced earth pressure. When the foundation pit excavation is shallow, the displacement of the top of the wall is the largest. However, with the increase of the excavation depth of the foundation pit, after the completion of the horizontal support construction, the displacement of the top of the wall remains the same or even moves outside the foundation pit, with the middle of the wall protruding into the pit and the displacement being the largest.

With the excavation of foundation pit, under the action of active earth pressure, the wall will be deformed and displaced. When the support has not been poured, the displacement of the wall decreases linearly along the depth direction. After that, due to the completion of the erection of the horizontal support, the horizontal displacement curve of the ground connecting wall becomes a bow shape with large middle and small two ends. For each side wall, the middle deformation is larger and the corners are smaller.
4. Conclusion
The supporting structure of the deep foundation pit project simulated in this paper is complex and irregular in shape, and its stress and deformation characteristics cannot be well simulated by using two-dimensional finite element method. The three-dimensional finite element model of foundation pit established in this paper regards soil, ground connection wall and horizontal support as an organic unified whole for analysis. In this way, not only can the stress and deformation of each node of the supporting structure system at each time analysis step in the process of foundation pit excavation be calculated, but also the internal force of the support can be more accurately analyzed. According to the actual situation of foundation pit engineering, the dynamic simulation of the construction process can also be carried out considering the working conditions of soil excavation and support erection step by step. Through the calculation and analysis, the numerical model can better simulate the complicated support form and the layered excavation condition of foundation pit.

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References
[1] Zhang, Q.Y. (2005) Application of bar system FEM for beam on elastic foundation in supporting design for a deep and large foundation pit engineering. Journal of Building Structures, 3, 114-117.
[2] Pei, G.H. Wu, J. Liu, J.J, Liang, B. (2004) Numerical modeling of seepage-stress coupling of deep foundation pit excavation. Chinese Journal of Rock Mechanics and Engineering, 23, z2: 4975-4978.
[3] Tu, Y. M., Ruan, C. Q., Zhao, X. Q., Li, S. M. (2006) Protecting technique for deep excavation of Wenzhon Grand Theater. Chinese Journal of Geotechnical Engineering, 28, 1: 59-62.
[4] Liu, Y.P. (2010) Design and optimization of double large-diameter arched beam support system in foundation pits. Chinese Journal of Geotechnical Engineering, 32, S1: 219-222.
[5] Wang, W. D., Wang, H. R., Xu, Z. H. (2012) Experimental study of parameters of hardening soil model for numerical analysis of excavations of foundation pits. Rock and Soil Mechanics, 8: 010.
[6] Finno, R. J., Tu, X. (2006) Selected topics in numerical simulation of supported excavations. In Numerical Modeling of Construction Processes in Geotechnical Engineering for Urban Environment, keynote lecture at the International conference of Construction Processes in Geotechnical Engineering for Urban Environment, London: Taylor& Francis.