Influence of Trough Excavation Study on Deformation of Deep Foundation Pit Support Structure in Water-rich Area

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Abstract. Based on finite element numerical calculation, calculation results of first support, trough excavation and over-excavation working conditions were compared in this paper. Analysis of deformation difference of retaining structure in water-rich and thick sand stratum was provided. Calculation results were compared with actual monitoring data, in order to explore the influence law of trough excavation on the horizontal deformation of retaining structure. The results show that the trough over-excavation soil exacerbates the lateral deformation of underground diaphragm wall, the cumulative maximum is 9.28mm and the process maximum is 10.45mm, 34.93% of the maximum underground diaphragm wall deformation. Conclusion of back pressure soil restrains the deformation of underground diaphragm wall can also be drawn, the process maximum is 6.44mm, 21.52% of the maximum underground diaphragm wall deformation. The design of the deep foundation pit retaining structure should be checked as far as possible according to the actual working conditions to reduce the engineering risk, ensuring that the design is economical, reliable and reasonable.

1. Introduction

Cross-river engineering is increasing with the development of transportation infrastructure[1], difficulties in the construction of deep foundation pits in water-rich area are not only more difficult and risky during construction, but also include tighter schedules. It is often required to complete the construction in the non-rainy season, and the river must be restored before the flood season. Actual construction will be difficult to match the design conditions.

When the soil layer of the deep water-rich pit is mainly sand, due to the poor cementing effect of sandy soil, uprush is extremely to happen[2], bringing great challenge to deep foundation pit engineering[3].

Technique of cross-river deep foundation pit engineering is rarely reported at present, especially for research on both cross-river and sand layer foundation pit construction.

As the earth pressure theory is highly dependent on experience, and is more susceptible to influence of geological conditions, construction conditions and meteorological factors, underground engineering is more risky than other structural engineering. For open-cut foundation pit, the safety and economy of enclosure design determine the success or failure of the project.

Whether the design condition of the foundation pit is consistent with the actual working conditions directly affects the conformity between the enclosure structure deformation value of the design calculation and the actual construction monitoring value, and thus affects the safety assessment.
Forced deformation of the deep foundation pit enclosure structure is controlled by the joint action of soil and supporting structure[4], different excavation processes are closely related to the deformation of the enclosure structure[5]. The calculation methods of underground structures mainly include load structure method (structural mechanics model) and stratum structure method (rock mechanics model) [6] and empirical analog model etc.. No matter which method is adopted, the larger the foundation pit depth is, the greater the design calculation error is[7]. Compared with load structure method, stratum structure method considers interaction between structure and stratum, and can analyze the internal force and structure deformation at each construction stage. In addition, in most cases, stratum structure method is difficult to adopt analytical calculation method, and numerical method is often adopted, especially for deep foundation pit engineering with multi-layer inner support. The stability of underground diaphragm wall is the premise of safety of foundation pit and surrounding environment[8]. Factors affecting the deformation of retaining structure such as the underground diaphragm wall include the surrounding environmental conditions, the retaining structure rigidity, the supporting structural parameters (stiffness, horizontal spacing, vertical spacing, etc.), etc.[9], especially for deep foundation pit with multi-channel support in water-rich thick sand stratum, the construction condition is very sensitive to the deformation of the envelope structure. Therefore, combining construction conditions to analyze the deformation of underground diaphragm wall is beneficial to ensure the rationality of envelope structure design, can achieve pre-control and process control, and effectively reduce or avoid early warning events. This paper relies on a deep foundation pit project of Guanqu Road in Beijing. Deformation of the retaining structure is predicted according to design conditions and construction conditions, actual monitoring results are also compared. On the basis of the difference, prediction method of the deformation of underground diaphragm wall will be explored, in order to provide reference for similar projects.

2. Project Overview
This foundation pit project runs from west to east across watercourse and levee of the northern canal, the project is about 21m deep, 33.2m wide and 240m long. The foundation pit in the river channel is constructed by staged cofferdam method. The water depth is about 2.5m during the survey, perched groundwater is locally distributed, and two layers of confined water are distributed in the deep sand layer.

The strata within the 70m depth below the ground level of the project site can be divided into three major categories: artificial accumulation layer, newly deposited layer and Quaternary sedimentary layer according to its sedimentary age and engineering properties. The soil of artificial accumulation layer is mainly silt soil filling and miscellaneous filling; The newly deposited soil layer is mainly composed of fine sand, silt layer and silty clay layer. The lithology of the Quaternary sedimentary layer is dominated by interaction layer of clay soil, silt soil and sand soil.

The foundation pit engineering adopts open excavation construction method. The main structure is a closed frame in the form of a grid. The enclosure structure uses 800mm thick underground diaphragm wall poured with C35P8 underwater concrete. Five supports are provided in the pit. The first support is 80*100 reinforced concrete support with a longitudinal spacing of 9m. The other four are φ800 steel pipe supports with a longitudinal spacing of 3m.

Typical section design scheme is shown in Figure 1.
3. Numerical Analysis of Excavation Scheme

3.1 Numerical Calculation Scheme

Typical section of the project is selected for numerical calculation. The constitutive model selects soil hardening (HS) model that can describe the soil stiffness more accurately and is proved that the effect is closer to reality through multiple engineering practices. The HS model can not only consider the shear hardening of the soil during loading, but also consider the compression hardening of the soil[10], it means that soil stiffness increases with increasing pressure. In the calculation, groundwater is considered in three times of precipitation in the absence of seepage mode.

In order to facilitate comparative analysis, this paper conducts calculation in three schemes, namely, design excavation condition, trough excavation conditions and overall over-excavation conditions. The various working conditions are shown in Figure 2, and the grid is shown in Figure 3.

The design excavation scheme (hereinafter referred to as “Scheme 1”) strictly follows the design scheme, the foundation pit will be excavated in layers, the bottom surface of each layer is located 300mm below the bottom level of each layer of support, and the support is erected in time.

The trough excavation scheme (hereinafter referred to as “Scheme 2”) to reserve a 2m wide platform on the inner side of the foundation pit as backpressure soil, and 1:1.5 slope excavation after the platform.

The overall over-excavation scheme (hereinafter referred to as “Scheme 3”) is the most unfavorable scheme, that is, the back pressure soil on both sides of the tank is not reserved, will be excavated directly to the bottom level of the trough compared with Scheme 2.

Among the three soil excavation schemes, Scheme 1 is the safest. First support and then digging, timely support, can effectively control the deformation of envelope structure; In Scheme 2, soil in the trough is over-excavated, however, this scheme is a common practice for the actual construction of long-supported foundation pits. Due to the influence of dense internal support on mechanical operation, it is difficult to strictly follow the design scheme. Scheme 2 is convenient for construction, and the back pressure soil has a certain supporting effect on the envelope structure, but the safety risk is larger than scheme 1. Scheme 3 can save a lot of construction time, but not conducive to construction safety.
3.2 Parameter Selection and Calculation Procedure

The soil conditions revealed during the construction process are basically the same as the survey reports. The soil layer parameters are shown in Table 1. For those parameters are not given in survey reports, the empirical value is selected.

The numerical calculation process is as follows: the first precipitation, water level dropped to 1m below the surface → establish underground diaphragm wall → excavate soil in ① site → set the first support → the second precipitation → excavate soil in ② site → set the second support → excavate soil in ③ site → set the third support → the third precipitation, water level drops to 1m below the bottom elevation of the foundation pit → …(Scheme 2: After the excavation of the soil 3 is completed, the second support is set.)

| Soil layer     | ρ(g/cm³) | Es(Mpa) | C(kPa) | Φ(°) |
|----------------|----------|---------|--------|------|
| Fill stratum   | 1.75     | 8       |        | 12   |
| Fine sand      | 2.00     | 43      | 0      | 30   |
| Fine sand      | 2.05     | 45      | 0      | 34   |
| Silty clay     | 1.97     | 9.7     | 28     | 12.3 |
| Fine - medium sand | 2.05 | 50 | 0 | 34 |
| Fine - medium sand | 2.05 | 65 | 0 | 35 |
| Fine - medium sand | 2.05 | 75 | 0 | 36 |
| Silt           | 2.03     | 27.7    | 15     | 30   |
| Fine - medium sand | 2.05 | 75 | 0 | 36 |
| Fine - medium sand | 2.05 | 85 | 0 | 36 |

| Es(Mpa) | Area(m²) |
|---------|----------|
| First   | 30000    | 0.80 |
| Second  | 206000   | 0.0394 |
| Third   | 206000   | 0.049 |
| Forth   | 206000   | 0.049 |
| Fifth   | 206000   | 0.0394 |
3.3 Analysis of Calculation Results

Figure 4 shows the horizontal deformation of the north side underground diaphragm wall in three calculation conditions (left wall in Figure 3). The five curves in each figure are the displacement distributions corresponding to different depths when the five-layer support is set. It can be seen that the top deformation of the wall is mainly caused by the first excavation of the topsoil. After the first support is set in time, the top of the wall is slightly deformed.

Figure 5 shows the mesh deformation map and the final horizontal deformation and bending moment envelope of the underground diaphragm wall after the excavation of the foundation pit to the bottom line magnified by 200 times. It can be observed clearly that the corresponding depth of underground diaphragm wall of each channel supports is smaller than the surrounding deformation, which further indicates that this numerical analysis is reasonable.

Horizontal deformation of underground diaphragm wall increases with the depth of excavation. The maximum horizontal deformation of the diaphragm wall after excavation to the elevation at the top of the floor and stabilization is 20.64mm, 29.12mm and 31.73mm, respectively. After excavation to the bottom line of the foundation pit, the deformation values are 24.84mm, 32.91mm, and 34.65mm, respectively, the maximum values are located at a depth of about 15 m below the surface.

Table 3 shows the maximum horizontal deformation of the underground diaphragm wall and the maximum impact of the process under each of the three calculation schemes.

![Figure 4. Horizontal deformation of underground diaphragm wall after support installation](image1)

![Figure 5. Horizontal deformation and bending moment envelope diagram of underground diaphragm wall magnified by 200 times](image2)

| Number of support installation | Scheme 1 | Scheme 2 | Scheme 3 |
|-------------------------------|----------|----------|----------|
| Maximum horizontal displacement | 7.14     | —        | 7.09     |
| Maximum process displacement  | —        | —        | —        |
Figure 6 shows the maximum incremental horizontal displacement curves of each procedure of underground diaphragm wall under the three schemes, the values corresponding to the 1-4 process are the maximum incremental horizontal displacement of the wall after the setting of the next support is completed compared with that of the previous support, the value corresponding to the 5th process is the maximum value of the horizontal displacement increment of the wall after excavation to the elevation of the bottom floor and soil stabilization compared with that when the fifth support is set.

4. Comparative analysis of on-site monitoring and numerical calculation

SINCO inclinometer is used to monitor the deep horizontal displacement of the retaining structure during the construction process, Figure 7 is the actual monitoring data curve of the underground diaphragm wall corresponding to the typical calculation section. The maximum value and maximum increment of each process are shown in Table 4.

Table 4. Actual monitoring data of maximum horizontal deformation and process displacement of underground diaphragm wall (mm)

| Process                  | Maximum horizontal displacement | Maximum process displacement |
|--------------------------|--------------------------------|------------------------------|
| First support is installed | 0.89                          | 6.99                         |
| Second support is installed | 7.74                          | 10.97                        |
| Third support is installed | 15.56                         | 7.04                         |
| Forth support is installed | 22.23                         | 14.74                        |
| Fifth support is installed | 29.70                         |                              |

During the actual construction process, the construction excavation and internal support setting timing and design working conditions may not be completely consistent, and there are various...
disturbances such as construction vehicles, which makes the numerical calculation impossible to be completely consistent with the actual monitoring.

There are many incentives for the deformation of the foundation pit retaining structure during construction, and the numerical calculation is difficult to cover all aspects, However, it can be seen that the negative horizontal deformation value occurring in the upper part of the envelope structure, the numerical calculation is basically consistent with the actual monitoring data trend, the maximum horizontal displacement of the underground diaphragm wall is also very close, moreover, since the installation of the third support, the horizontal displacement on the upper part of the diaphragm wall also decreases in numerical calculation scheme 2, which is consistent with the actual monitoring, therefore, there are good reasons to believe that the numerical calculation method has research value and the analysis result is credible.

5. Analysis and Conclusion

(1) Influence of over-excavation of trough excavation scheme on horizontal deformation of underground diaphragm wall

In scheme 1, only after the third support setting is completed, the "bow" character deformation is obvious, before this process, deformation of the underground diaphragm wall is not large, the maximum variation is about 0.9mm, and the cumulative deformation maximum is 7.4mm, the excavation of soil process has the largest cumulative variation of the wall deformation at the depth of 6m and 16m below the surface, and the change value is only 1.7~2.2mm, that is, according to the ideal first support and excavation, the whole system is safe when excavating the first three layers of soil; After excavating the fifth layer of earthwork and setting the fifth support, the horizontal deformation of the wall is 18.67mm, which is 62% of the control value of 30mm; Excavation to the top level of bottom plate, the horizontal deformation value is 20.64mm, and the difference between the control values is about 10mm.

In scheme 2, the deformation of the wall is obvious when the second support is installed, indicating that the first soil over-excavation has a great impact on the safety of the system.

Combined with the deformation curve and the difference of the process displacements of the two schemes in Table 3, it can be known that the influence of the over-excavation under the second support on the wall deformation exceeds 3 mm, and the influence distribution range is wide, mainly located 5m~17m below the surface; The maximum value of the horizontal displacement of the two schemes is reduced by 3mm, which is the cumulative influence of the over-excavation in the previous step. It can be seen that the maximum impact of the over-excavation on the wall under the third support is 5.57mm, and the same influence range is larger; After the third support is set, the influence degree of the two schemes on the wall is close, that is, the difference of the process displacement is not obvious, and the main influence distribution range is 13m~18m below the surface, this is because the support, especially the third and fourth support, has been fully functional and the soil under the fifth support has less over-excavation.

Compared with design excavation scheme, the cumulative maximum of the influence of trough excavation scheme on the horizontal displacement of the underground diaphragm wall is 9.28 mm, and the maximum value of process is 10.45 mm, the maximum value of the process occurs when the fifth soil is over-excavated and the fifth support is set, which is 34.93% of the maximum deformation of the wall.

It can be seen from figure 6 that in scheme 1, after the excavation of the fourth layer of soil and the installation of the fourth support, the deformation of the wall is the largest, reaching 7.1 mm; In scheme 2, after the excavation of the fourth layer of soil (the third over-excavation) and the installation of the third support, the deformation of wall is the largest, and the maximum value is 8.57mm. According to the analysis, the trough excavation scheme can promote the rapid function of the support to suppress the deformation rate compared with design excavation scheme.

(2) Effect of reserved back pressure soil on controlling the deformation of underground diaphragm wall
It can be seen from the graph that the shape of the horizontally deformed "bow" of the underground diaphragm wall after the second support setting is completed is obvious in scheme 3, and the maximum deformation of the wall is different from scheme 1 and scheme 2, not at the top of the wall; According to Table 3, the displacement of scheme 2 in this stage is 1.53 mm smaller than that of scheme 3, this value is controlled by reserved back pressure soil; After setting the third support, the displacement of scheme 2 is smaller than scheme 3 by 2.09mm; After setting the fourth support, the displacement of scheme 2 is smaller than scheme 3 by 4.45mm, that is, in this stage, the support effect of the back pressure soil on both sides of the trough is more significant. After that, the deformation trend of the wall is slowed down compared with the other two schemes.

It can be seen from Figure 6 that the scheme 3 has the largest deformation increment after the fourth layer of soil is excavated and the fourth support is set, reaching 11.38mm, after that, the deformation rate slows down rapidly, but the rate is slowed down after setting the third support in scheme 2.

From the comparative analysis, it can be seen that the reserved back pressure soil is very beneficial to the control of the retaining structure deformation in the trough excavation scheme, the maximum value of the process is 6.44mm, which occurs when the fourth soil is over-excavated and the fourth support is set, which is 21.52% of the maximum deformation of the wall.

Through analysis and calculation, the following conclusions are drawn:

(1) The numerical calculation results are not completely consistent with the actual monitoring data, but the deformation trend is consistent, and the deformation maximum value and position of the enclosure structure are close to the actual working conditions, after the third support is set, the deformation rate of the wall is obviously slowed down, so the numerical calculation results are considered to be credible, and the three excavation schemes have research significance.

(2) Under the conditions of water-rich area and thick sand stratum, the cumulative value of influence of over-excavation on the horizontal displacement of the underground diaphragm wall in trough excavation scheme is 9.28 mm, the maximum value of process is 10.45 mm, 34.93% of the maximum deformation of the wall.

(3) Under the conditions of water-rich area and thick sand stratum, the cumulative maximum value of the back pressure soil on both sides of the trench is 6.44mm, accounting for 21.52% of the final deformation of the wall.

(4) The effect of the excavation of the trough excavation on the deformation of wall and the suppression effect of back pressure soil on the deformation of the wall mainly occur in the excavation of the third and fourth layers of soil, and the third and fourth support processes are set.

(5) It can be seen from the numerical calculation of Figure 3 that the wall deformation will be further aggravated when the floor soil is excavated, so that the horizontal displacement of the wall is likely to exceed the control value of 30 mm. In this case, the deformation can be controlled by pouring the floor while excavating.

The finite element simulation analysis of the excavation process and the monitoring results of the foundation pit deformation show that the design scheme of the foundation pit is safe and economical, but the actual construction is difficult to fully match the theoretical conditions. Excavation according to the trough scheme of Beijing Municipal Technical Regulations for Supporting Foundation Pit Engineering (DB11 940-2012), the maximum deformation of retaining structure is significantly increased. The foundation pit support design should be combined with the construction conditions, check the actual working conditions as much as possible, provide a reasonable foundation pit monitoring deformation control index, and make an accurate evaluation of the construction safety of the envelope structure system.

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