Empirical Method and Finite Element Analysis of Deep Foundation Pit Excavation in Ningbo Soft Soil

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Abstract. How to analyze and judge the excavation deformation of deep foundation pits in cities has become an urgent problem to be solved. Through the analysis of the excavation monitoring data of a deep foundation pit of a station on Ningbo Metro Line 3, the characteristics of horizontal displacement and surface settlement of the ground-connected wall during the foundation pit excavation in Ningbo soft soil area are obtained. And to compare and analyze the monitoring data by the empirical statistics method and the finite element method. Analysis shows that both can predict the deformation trend of foundation pit. However, due to the regional nature of the deep foundation pit engineering, the prediction accuracy of the empirical curve is poor. Compared with the empirical statistical method, the finite element method has better prediction accuracy, but the finite element method is more complicated. The advantages of the two methods can be applied in the project. In the study of deformation prediction of deep foundation pits, a more in-depth study of the combination of the two methods can be carried out.

1. Introduction

In recent years, with the rapid development of urban rail transit and the expansion of underground space development, a large number of subway station deep foundation pit projects have been established. Moreover, urban areas are densely populated and there are many pipelines, and the environmental conditions of foundation pit engineering are becoming increasingly complex. Especially in China's southeast coastal soft soil area, the soil has high water content, high sensitivity, large void ratio, low shear strength, low bearing capacity and easy to be disturbed. Therefore, urban foundation pit engineering, especially urban foundation pit engineering under soft soil quality conditions, faces severe challenges [1-2].

At present, there are two main methods for studying the deformation of the retaining structure and the displacement of the surrounding soil caused by excavation of deep foundation pits. One is the method of empirical statistical analysis by collecting measured data. For example, Peck [3], Blackburn et al. [4], Ou et al. [5], Clough et al. [6] studied the soil deformation caused by foundation pit excavation, and Mana et al. [7], Kung et al. [8] studied the deformation of the retaining structure caused by excavation of foundation pits.” Another main method is finite element analysis. Youhai Yang et al. [9] used the finite element analysis method of elastic foundation beam system to analyze the structural characteristics of deep foundation pit support of Qiutao Road Station in Hangzhou Metro. Shuajun Liu et al. [10] used the numerical analysis method of considering the HS model of the soil to...
analyze the construction process of the open pit foundation pit of the cross-river section of the cross-river tunnel. Liqiao Cao et al. [11] used the ABAQUS finite element software to establish a three-dimensional foundation pit model in soft soil area, and obtained the basic law of foundation pit bulge during foundation pit excavation and precipitation.

Most of the above studies are single analysis of engineering cases using empirical or finite element methods, and there are still few studies using both methods in engineering cases. This paper relies on the deep foundation pit engineering of a subway station in Ningbo soft soil area. Based on the HS model's Plaxis finite element software and other empirical results of deep foundation pit excavation similar to the soil properties in the soft soil area of Ningbo, analysis the on-site monitoring data during the excavation of deep foundation pits. Focus on analysis of retaining structure deformation and surface settlement during foundation pit excavation, and provide reference for similar foundation pit engineering design and construction.

2. Project overview

2.1 geological condition

The metro station is located in the Ningbo fault basin, which belongs to the landform type of the Coastal rush Lake type plain. The terrain is flat, the silt soil is thick, the water is weak, and the mechanical properties are worse than other soft soil areas. Table 1 compares the parameters of the main soil layer at the station location with the main soil parameters of a foundation pit in Shanghai and Hangzhou soft soil areas [12-13]. It can be found that the soil moisture content and void ratio of this station are larger than those of Shanghai and Hangzhou soft soil areas, and the soil quality is softer.

| location                           | Moisture content w/% | Pore ratio e | Natural severity |
|-----------------------------------|----------------------|--------------|-----------------|
| This station                      | 41.5                 | 1.16         | 17.6            |
| a foundation pit in Shanghai      | 28.3                 | 0.87         | 18.8            |
| a foundation pit in Hangzhou      | 29.5                 | 0.84         | 18.8            |

2.2 Foundation pit design and excavation construction plan

This deep foundation pit project is a metro station of Ningbo Metro Line 3. The station is a two-story single-column reinforced concrete box structure with a clear excavation method. The first layer of excavated soil is 0~-5.8m; the second layer of excavated soil is -5.8m~-9.0m; the third layer of excavated soil is -9.0m~-12.4m; the fourth layer of excavated soil is -12.4m~-15.3m; the fifth layer of excavated soil is -15.3~ foundation pit. Figure 1 shows the standard section of the foundation pit. The standard section has a buried depth of 17.76m and a standard section width of 21.70m. It is made of 800mm thick underground continuous wall structure (C35P8 underwater concrete). The standard section wall depth is 36m. The foundation pit of the southern end of the well is about 19.51m deep and the wall depth is 40m. The foundation pit of the northern end of the well is about 19.21m deep and the wall depth is 40m. Foundation pit dewatering construction ahead of foundation pit excavation for 1 month, The bottom of the pit is made of pumping and skirt reinforcement. The reinforcement depth is 3m below the bottom of the pit. The support settings for the foundation pit are shown in Table 2.
2.3 Foundation pit design and excavation construction plan

In order to comprehensively analyze the deformation behavior during the construction of the deep foundation pit, a number of monitoring work was carried out during the construction of the foundation pit. This paper focuses on the horizontal displacement of the surrounding wall of the retaining wall. Figure 2 shows the layout of the foundation pit monitoring project and monitoring points. The foundation pit is a regular symmetrical shape, so the data of the monitoring points on the side of the foundation pit is analyzed.

3. Monitoring data and its empirical analysis

The time period for collecting the excavation monitoring data is: the site monitoring data from the start of the excavation preparation to the completion of the excavation of the foundation pit, a total of 160 days. For the convenience of description, the meaning of each parameter in this paper is shown in Figure 3.
3.1 Horizontal displacement of diaphragm wall and its empirical statistical comparison

Figure 4. (a) shows the data of each measured slope point when the pit is excavated to the bottom. The positive value is in the pit and the negative value is outside the pit. It can be seen from Fig. 4. (a) shows the position of the maximum horizontal displacement of the wall is near the bottom of the pit. The maximum horizontal displacement of the diaphragm wall is CX-13, which is located in the middle of the long side of the foundation pit, with a horizontal displacement of 66.66mm and a depth of 14.5m. The minimum horizontal measuring point of the underground continuous wall is CX-9, which is located in the middle of the end of the foundation pit, with a horizontal displacement of 25.01mm and a depth of 16m. Table 3 shows the comparison range of $d_{hm}/H$. It can be seen that the $d_{hm}/H$ variation range of the on-site monitoring data is within the variation range of the deep foundation pit in Shanghai area by Zhonghua Xu et al. [9], not in Singapore and Taipei by M. Long [15] and C. Ou et al. [5] Within the scope of regional changes.

Zhonghua Xu et al. [14] statistics $d_{hm}$ of foundation pit in Shanghai area is within the range of $H-5$--$H+$. The $d_{hm}$ of the foundation pit is located above the base pit. It can be seen from Fig. 4. (a) that when the foundation pit is excavated to -5.8m, -9.0m, -12.4m, the maximum horizontal displacement depth of the wall is 10.5m, 11.5m, 13.5m below the excavation surface, respectively. And when the foundation pit is excavated to -15.3m and -17.7m, the maximum horizontal displacement depth of the wall is 14m and 14.5m above the excavation surface. This might be when the excavation depth is small, the bottom of the pit is in (1) Muddy clay and (2) Muddy clay. The passive soil is poor in nature, the upper support stiffness is large, and the deformation is easy to develop downward. With the increase of excavation depth, the lower soil layer is reinforced, the nature of the passive soil tends to be good, and the deformation development rate becomes slower, so the $d_{hm}$ position is above the bottom of the pit.

Table 3 Comparison of $d_{hm}/H$ range of variation

| Data Sources            | $d_{hm}/H$ variation range (%) |
|-------------------------|--------------------------------|
| Field monitoring data   | 0.13--0.38                     |
| Zhonghua Xu et al.      | 0.1--1.0                       |
| M.Long and C.Ou et al.  | 0.33--0.87                     |
3.2 Surface settlement and its empirical statistical comparison

The ground settlement of each measuring point when the foundation pit is excavated to the bottom is shown in Fig. 5(a). Surface subsidence increases first and then decreases. The $d'_{m}$ is -60.2mm (D12-4) and the distance from the foundation pit is 27m. Except for the D12 section, the maximum settlement position is about one excavation distance from the foundation pit, it can be seen that the change value of the D12 section is larger than other points. This is because the D12 section is located in the river backfilling position and is affected by the soil disturbance. The maximum ground settlement value of this foundation pit is 0.34% $H$, which is consistent with the change value of 0.1% $H$–0.8% $H$ of the ground settlement of deep foundation pit in Shanghai according to Weidong Wang et al. [16]. Fig. 5(b) shows the variation of surface settlement along the excavation depth of the intermediate section D13 of the long side of the foundation pit. It can be seen that the surface settlement at each point increases with the increase of the excavation depth. And when excavated to - 5.8m, - 9.0m, - 12.4m, - 15.3m and the bottom of the foundation pit, the maximum ground settlement point is D13-3, which is 17m away from the foundation pit, approximately equal to the excavation depth of the foundation pit.
3.3 Empirical statistical curve

In addition to the variation range of the deformation peak, the empirical statistical method also gives an empirical statistical formula for predicting the deformation curve. At the International Soil Mechanics Conference in 1969, Peck [3] proposed a surface settlement curve in the form of Gauss function (1). Where \(d_{v,\text{max}}\) is the maximum surface settlement value, \(i\) is the distance from the center of symmetry of the sedimentation curve to the calculated point. Formula (2) is a form of a Gauss function in which \(a\), \(b\), and \(c\) are real constants. In addition to the Peck curve, the ground subsidence prediction formula considering the eccentricity \(x_0\) of the settlement tank proposed by Min Yang et al. [17], where \(k\) is the settlement correlation coefficient and \(x_0\) is the eccentricity of the groove. Formula (4) Chenrong Zhang et al. [18] statistic of the horizontal displacement variation formula of the ground-connected wall on the symmetry plane of the foundation pit in Shanghai, all in the form of Gauss function. Whether the following empirical statistics prediction curve can be used to predict the deformation curve of this foundation pit requires further comparative analysis.

\[
\begin{align*}
    d_v(x) &= d_{v,\text{max}} e^{-\frac{x^2}{2i^2}} \\
    f(x) &= ae^{-\frac{(x-b)^2}{2c^2}} \\
    d_v &= d_{v,\text{max}} e^{k(x-x_0)^2} \\
    d_h &= d_{h,\text{max}} e^{-1.5 \left( \frac{H}{H'-1} \right)^2}
\end{align*}
\]

4. Comparative Analysis of Empirical Statistics and Finite Element Method

4.1 Finite element model establishment and calculation

Different from the empirical statistics method, the finite element method can simulate the whole process of excavation according to the specific project, and the deformation result of the foundation pit can be obtained from the calculation result of the finite element. In order to compare the effects of the empirical statistical curve, the finite element method and the monitoring data were used for comparative analysis. This section will use PLAXIS finite element software to build a numerical model to simulate the whole process of foundation pit excavation. Then, the combination of empirical statistics and finite element method is used to analyze and compare the on-site monitoring data.

The HS model (soil hardening model) in PLAXIS software can consider the hardening characteristics of soft clay and adopt different loading/unloading modulus, which can better simulate the influence of stress history and stress path on soil deformation. It is suitable for numerical simulation of excavation of foundation pit under sensitive conditions [19-20]. Therefore, the soil constitutive model is simulated by HS model. Combined with the engineering survey report and the research results of Wang Weidong et al. [19], Song Guang et al. [20], the soil parameters are shown in Table 4. In the model, the "wall" unit simulation, the crown beam and the raft support are simulated by the "beam" unit, and the steel support is simulated by the "bolt" unit. The material parameters are set as shown in Table 5. The calculation model of the foundation pit is shown in Fig. 6.

| Soil        | \(E_{\text{ox,ref}}\) /MPa | \(E_{\text{ref}50}\) /MPa | \(E_{\text{ur}}\) /MPa | \(C_{\text{ref}}\) /KPa | \(\phi\) /° | \(R_f\) |
|-------------|-----------------------------|---------------------------|------------------------|-------------------------|------------|--------|
| ① Miscellaneous fill | 5.00                        | 5.00                      | 20.00                  | 10.0                    | 28.0       | 0.50   |
| ① Clay      | 4.63                        | 4.63                      | 23.15                  | 5.6                     | 26.7       | 0.76   |
| ① Muddy clay | 2.40                        | 3.60                      | 19.20                  | 6.7                     | 24.7       | 0.83   |
| ② T silt    | 2.07                        | 3.10                      | 16.56                  | 5.9                     | 23.8       | 0.83   |
| ② Muddy clay | 2.23                        | 3.35                      | 17.84                  | 6.9                     | 23.7       | 0.83   |
Table 5 Parameters of material

| Material name            | $E$ ($kN/m^2$) | $\gamma$ ($kN/m^2$) | $V$ | $EA$ ($kN$) |
|-------------------------|---------------|---------------------|-----|-------------|
| Diaphragm Wall          | $3 \times 10^7$ | 22                  | 0.15| —           |
| Crown beam              | $3 \times 10^7$ | 0                   | —   | —           |
| Concrete support        | $3 \times 10^7$ | 0                   | —   | —           |
| 609 Steel support       | —              | —                   | —   | $2 \times 10^6$ |
| 800 Steel support       | —              | —                   | —   | $2.5 \times 10^6$ |

4.2 Horizontal displacement curve of diaphragm wall

In order to compare the horizontal displacement of the wall in the empirical statistics and numerical simulation, at the same position as the measuring point CX-13, the data of 43 measuring points are taken to draw the horizontal displacement curve of the ground wall. Among the existing empirical statistics, the geological conditions in Shanghai are similar to those in Ningbo. Therefore, the empirical curve selects the horizontal displacement variation formula (4) of the connected wall of the symmetry plane of the foundation pit in Shanghai area as summarized by Chenrong Zhang et al. [17] mentioned in Section 3.3 of this paper. The horizontal displacement curve of the ground wall obtained by substituting the measured maximum horizontal wall displacement $dhm$ into (4) is shown in Fig. 7. It can be seen from the figure that the simulated value, the empirical prediction curve and the measured curve are all in the shape of "large in the middle, small in both ends". In the lower part of the $dhm$ position, the empirical deformation curve of the ground wall is larger than the measured curve, which is about twice the measured value. Compared with the empirical prediction curve, the numerical simulation results are more closely matched with the measured values, and the simulated values and the measured values almost coincide with each other in the range of 10 m below the wall. Therefore, it can be seen that the finite element calculation is superior to the prediction of empirical statistics.
4.3 Surface settlement curve

Surface settlement is also an important indicator in the design and construction of foundation pit engineering. There are many results in using empirical statistics to predict surface subsidence, but the empirical statistics in Ningbo are limited. There are no statistical conclusions in Ningbo. Therefore, the surface settlement envelope of Shanghai foundation pit excavation similar to that of Ningbo area is selected here by Weidong Wang et al. [16]:

\[
\begin{align*}
\frac{d_v}{H} &= 0.5 + 0.8 \frac{x}{H} \quad (0 \leq \frac{x}{H} \leq 0.5) \\
\frac{d_v}{H} &= 1.167 - 0.533 \frac{x}{H} \quad (0.5 \leq \frac{x}{H} \leq 2.0) \\
\frac{d_v}{H} &= 0.2 - 0.05 \frac{x}{H} \quad (2.0 \leq \frac{x}{H} \leq 4)
\end{align*}
\]

(5)

and compared with the measured values. In addition, the curve of the surface settlement data with the same position as D13 in the finite element model is extracted. For comparison, surface settlement is excavated with excavation depth for dimensionless treatment. The horizontal axis is the ratio of the distance from the foundation pit \(x\) (m) to the excavation depth \(H\) (m), and the vertical axis is the ratio of the settlement \(d_v\) (m) to the excavation depth \(H\) (m). Figure 8 is a schematic diagram of the curve comparison of the dimensionless surface settlement.

Figure 8 Comparison in normalized ground settlement curves

It can be seen from the figure that the deformation curves of the measured values, the simulated
values and the empirical statistics are all concaves of the “thin” after the “drum”. The main surface settlement occurred within 2 times the excavation depth from the foundation pit. The maximum settlement point of the measured value is about 1 times the excavation depth from the foundation pit. The maximum settlement point of the simulated value is about 0.75 times from the foundation pit, and the maximum settlement point of Wang Weidong's distribution curve is at a depth of 0.5 times the excavation depth from the foundation pit. The maximum surface settlement of the simulated value is -50.02mm, the measured value is -60.20mm, the error is 16.9%, and the maximum settlement value of Wang Weidong's settlement envelope is about 3 times of the measured value, and the error is much larger than the simulated value. Through comparative analysis, it can be seen that the results of finite element and empirical statistics on the general settlement trend are similar to the measured values. However, in terms of fitness, the finite element calculation results are better than the predictions of empirical statistics.

5. Conclusion and Prospect

Based on the foundation pit project of a metro station in Ningbo soft soil area, this paper analyses the field monitoring data. The empirical statistical method and finite element simulation method were used to analyze the horizontal displacement and surface settlement of the grounding wall during the excavation of the foundation pit and compare it with the on-site monitoring data. conclusion are as below:

(1) Through the comparative analysis of the on-site monitoring data, the characteristics of the deep excavation deformation of the soft soil in Ningbo are obtained: The maximum horizontal displacement position of the wall is above the base of the foundation pit; the maximum value of the settlement of the foundation pit during excavation is the distance from the foundation pit to an excavation depth; the surface settlement and the horizontal displacement of the ground wall are both "two small, medium large" deformation curves.

(2) By comparing the field monitoring data with the empirical statistics of other soft soil areas, it can be found that the empirical statistics can predict the general deformation trend. On the specific deformation curve, the soft soil area of Ningbo is different from other soft soil areas, which indicates the regionality of empirical statistics. In addition, although the geology of Ningbo soft soil area is worse, the peak value of foundation pit deformation is within the range of other soft soil areas such as Shanghai. It is indicated that the deformation control construction process adopted in this project is feasible.

(3) Through the comparative analysis of the finite element method and the empirical statistical method, it is found that the finite element method has higher prediction accuracy for the foundation pit deformation than the empirical prediction curve. However, the finite element method is obviously more complicated in operation than the empirical statistics method. From the previous analysis, it can be seen that the application of the two methods is independent. How to combine the two methods to obtain more accurate predictions, such as using empirical statistical conclusions to guide the model establishment and parameter optimization of the finite element method, is a direction that can be further considered and studied.

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