Research on Deformation Characteristics of Foundation Pit Support Structure

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Abstract. Based on the theory of Bolton system stiffness, the factors of foundation pit excavation in Changsha area are analyzed, and an empirical formula is proposed. Taking Changsha Metro Line 3 as the background, Finite difference software Flac3D is adopted to simulate the excavation and analyze the law of horizontal displacement, the relationship between the system stiffness and the lateral displacement of the retaining structure is discussed. The results show that: 1) With the increase of the excavation depth of the foundation pit, the horizontal displacement of the retaining structure is small at both ends, and the middle is large, showing a "bow" type; 2) Based on the data of foundation pit excavation of six stations in Changsha, the empirical formula for predicting the lateral displacement of retaining structure is given.

1. Introduction
Subway is an important transportation way to solve the problem of urban traffic congestion and people's comfortable travel [1]. Subways in big cities such as Beijing, Guangzhou, Shanghai and Shenzhen have been running for years. During the construction of subway station, a large number of deep excavation has been built. Firstly, based on the analysis of the influence factors of the foundation pit deformation, the relationship between the deformation and stiffness is analyzed by Boldon system stiffness. Then the three-dimensional dynamic numerical simulation of the deep Foundation pit is carried out to analyze the horizontal displacement. some meaningful conclusions are obtained, which can provide reference for the design and construction of the foundation pit.

2. Study on system stiffness of foundation pit
Clough [2] proposed an empirical expression for the comprehensive stiffness, which can be used to estimate the normalized lateral displacement of the walls \( \delta_{hm} / H \):

\[
\eta = EI / \left( \gamma_w h_{ave}^3 \right)
\]  

(1)
EI: bending stiffness of foundation pit retaining structure with unit length; \( \gamma_w \): severity of water per unit volume; \( h_{ave} \): vertical average spacing; \( \delta_{lam} \): maximum lateral displacement of wall; \( H \): Depth of foundation pit excavation.

In the stiffness of Clough system, the influence of soil strength on composite stiffness is not taken into account. Assuming that the foundation excavation only affects the soft soil layer, the hard soil below will not be affected, and the thickness of the soft soil layer is \( C_{max} \), Osman[3] defines the wavelength of soil deformation caused by excavation:

\[
\lambda = \alpha s \tag{2}
\]

\( \alpha \) is the coefficient of deformation for the soft soil; \( s \) is the distance from the bottom to the toe of the foundation pit.

\[
\lambda_n = C_{max} - h_{n-1} \tag{3}
\]

\( \lambda_n \) is the deformation wavelength generated by excavation of layer \( n \); \( h_{n-1} \) is the vertical burial depth supported by \( n-1 \).

Bolton[4] takes into account the influence of soft soil and bracing position on the system stiffness, and uses the deformed wavelength \( \lambda^* \) to replace the vertical mean spacing of bracing \( h_{ave} \):

\[
\eta^* = EI / (\gamma_w \lambda^*) \tag{4}
\]

The data of 23 effective monitoring points for lateral displacement of envelope structures at six stations of Changsha Metro Line 2 and Line 3 are selected. The relevant parameters are statistically shown in the table below. \( \lambda_2 \) is deformation wavelength caused by excavation of second layers of soil; \( \delta_{lam} \) is the maximum displacement of retaining structure after excavation of second layers of soil.

| Number | Name                  | Number of points | \( H/m \) | \( EI/(\text{MPa} \cdot \text{m}^3) \) | \( \lambda_2 \) | \( \delta_{lam} \) |
|--------|-----------------------|-----------------|----------|---------------------------------|-----------------|-----------------|
| 1      | Jintai Square [5]     | 3               | 17.31    | 1885                            | 19.84           | 3.59            |
| 2      | Yuan Jialing [6]      | 5               | 18.75    | 1885                            | 20.75           | 3.45            |
| 3      | Trade Fair [7]        | 2               | 16.54    | 2880                            | 21.3            | 3.19            |
| 4      | Wuyi Road [8]         | 6               | 28.6     | 2218                            | 31.8            | 6.43            |
| 5      | Huangxing Square [9]  | 4               | 18.75    | 1280                            | 22.25           | 3.95            |
| 6      | Changsha Station [10] | 5               | 24.00    | 1280                            | 26.00           | 5.66            |
It shows that the lateral displacement of the retaining structure of the foundation pit changes obviously with the increase of stiffness. The power function can be used to fit the relationship:

$$y_{\text{Bolton}} = 0.734 \left[ \frac{EI}{\gamma_w \lambda^4} \right]^{-0.198}$$  \hspace{1cm} (5)

Fitting degree of curve $R^2$ is 0.96, which shows that the relationship between them is good. From the fitting curve, it can be concluded that the normalized maximum lateral displacement of the retaining structure of the foundation pit decreases obviously with the increase of the comprehensive stiffness, and the lateral displacement of the foundation pit tends to be stable gradually when the stiffness increases to a certain range.

3. Numerical model

Changsha railway station is located in the downtown area of the central city. This station is the underground three double pillar island platform station, the station outsourcing total length 187.6m, the standard section outsourcing total width 23.7m. The station buried deep 23.61m, the roof covered with 3.3m. In order to simplify the calculation, the excavation of the south side of the station is selected, the foundation pit is divided into a shield well and a part of the standard section. the south side of the foundation pit is an irregular polygon, the average length is 24m, the average width is 28m and the excavation depth is 24m. According to the saint vinan principle and reference, the influence range is 3~5 times excavation depth, the whole model is 270m×105m×96m. The top surface of the model is free, the bottom surface is fixed constraint, and the remaining surfaces add the normal constraint. Numerical model is shown in Figure 1.
calculation parameters are obtained from geological detailed survey reports in Table 1. The reinforced concrete support and steel support are simulated by beam element. The constitutive model adopts linear elastic material. The retaining structure is a cast-in-place pile, which is simplified as retaining wall according to the principle of rigidity equivalent. The density is taken as 2200 kg/m³, the elastic modulus E is 16GPa, and Poisson's ratio is 0.2. The connection between the support structures of different structural types in the model is realized by the method of sharing the nodes.

Table 2. Geotechnical parameters

| soil                  | depth/m | γ/(kN/m³) | c/kPa | ϕ/(°) | K/MPa | G/MPa |
|-----------------------|---------|-----------|-------|-------|-------|-------|
| Miscellaneous fill    | 5.2     | 17.5      | 10    | 18    | 4.76  | 1.47  |
| Silty clay            | 3.4     | 18.6      | 30    | 15    | 4.44  | 1.81  |
| Boulder               | 3.4     | 19.5      | 0     | 32    | 17    | 5.3   |
| Residual silty clay   | 6.4     | 20        | 30    | 15    | 4.44  | 1.81  |
| Strong weathered siltstone | 7   | 22.5      | 35    | 25    | 30    | 22.5  |
| Middle weathered siltstone | 68 | 25.5      | 300   | 25    | 158   | 68.7  |

According to the actual construction process of foundation pit excavation, the step-by-step excavation and support are carried out by means of analytical steps. The entire supporting structure of the foundation pit is shown in Figure 2. The object of this paper is the horizontal displacement of the retaining structure. According to the geometry of the simulated foundation pit, the representative midpoint of the shield well and the standard section 1 are selected as the horizontal displacement monitoring objects of the retaining structure.

4. Analysis of calculation results

In Fig.4, the curves of the horizontal displacement of the two retaining piles along the wall are shown in the foundation pit. It can be clearly seen that the horizontal displacement of the maintenance structure changes with the excavation step. Each of the curves in Figures 4 corresponds to each of the excavation steps. It can be seen from the curves that the horizontal displacement of the foundation pit maintenance structure is small at both ends and large in the middle. The reason is that the foundation pit excavation causes the soil outside the pit to form active earth pressure on the retaining pile, resulting in the retaining pile move inside the foundation pit. In the initial stage, the horizontal displacement changes little; as the excavation depth increases, the horizontal displacement increases gradually, the pile deformation is “bow” type, and the maximum displacement point has a decreasing trend.

Figure 4. Horizontal displacement
Combined with the influence of the shield mid-point and standard section support structure erection on the retaining pile, the law is obtained: when the foundation pit is completed, the maximum horizontal displacement of the pile is approximately 0.58H (H is the height of retaining wall).

The lateral displacement of the shield well pit and the standard section foundation pit is predicted by equation (6). The comparison between the numerical calculation value and the predicted value is shown in the following table:

| System Stiffness | Numerical Value | Theoretical Value | Monitoring Value |
|------------------|-----------------|-------------------|------------------|
| Shield well      | 237             | 5.72              | 5.59             | 5.41             |
| Standard section | 213             | 5.93              | 5.77             | 5.66             |

For the shield well pit, the numerical simulation after the second excavation is 5.7mm, the predicted value is 5.59mm, which is 5.7% and 3.3% respectively compared with the measured values; for the standard section foundation pit, after the second excavation The numerical simulation calculated value was 5.9 mm, and the predicted value was 5.77 mm, which was 4.8% and 1.9% different from the measured values. Through the above comparison, the accuracy of theoretical calculations and numerical simulation calculations is shown. However, in practical applications, the numerical simulation modeling calculation is adopted, the calculation parameters are considered to be complicated and the calculation takes time, and the theoretical calculation value can be quickly calculated with considerable precision, and the system stiffness of the foundation pit gives a quick assessment and is more convenient and efficient.

5. Conclusion

Based on FLAC3D finite difference software and system stiffness, the engineering examples of deep foundation pit excavation of metro station under complex support structure are analyzed, The main conclusions are as follows:(1) Based on evaluating the data of system stiffness, the empirical formula for predicting the lateral displacement of retaining structure is given;(2) After the second support erection is completed, the horizontal displacement of the pile top tends to be stable and does not vary with the depth of excavation; (3) Due to numerous factors affecting the stability of the foundation pit, it is recommended to strengthen the monitoring work during the construction process to ensure structural safety.

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References

[1] J. Liu, H.L. Yao, J.X. Ren, Monitoring and numerical simulation of deformation of retaining structure in subway station foundation pit, Rock. Soil. Mech. 31 (2010) 456-457.
[2] G.W. CLOUGH, E.M. SMITH, B.P. SWEENY. Movement control of excavation support systems by iterative design, Proc. Found. Eng. 2 (1989) 869-884.
[3] A.S. OSMAN, M.D. BOLTON, Ground movement predictions for braced excavations in undrained clay, J. Geotech. Geoenviron. Eng. 132 (2006) 465-477.
[4] BOLTON M D, LAM S Y, VARDANEGA P J. Ground movements due to deep excavations in Shanghai: Design charts, Front. Struct. Civ. Eng, 2014, 8 (3) 201-236.
[5] W. Deng, Optimization of Foundation Pit Support Design for Jintai Square Station of Changsha subway, Highw. Eng. 36 (2011) 91-97.
[6] W. Wang, Research on Changsha Metro Line 2 yuan Ling Station foundation pit stability assessment and support technology, Cent. South Univ. (2012) 30-34.
[7] R. Sun, Foundation pit supporting design and its stability study of Changsha metro line 3
QiMao avenue station, Hunan Univ. Sci. Technol. (2016) 51-55.

[8] M. Hu, Study on the Construction Technology of Excavation Engineering and Supporting Structure for the Deep Foundation Pit in Subway Station Wu Yi, Changsha Univ. Sci.& Technol. (2012) 63-66.

[9] D.W. Gong, Research on the Foundation Pit Construction Technology of Changsha Metro Station in the Water-rich Sandy Cobble Strata of Densely Built-up Areas, Cent. South Univ. (2013) 39-37.

[10] Z. Wang. Research on the influence of construction disturbance about new subway foundation pit docking with existing line seamlessly, Natl. Univ. Def. Technol. (2018) 31-38.