

Deformation and Sensitivity Analysis of Lateral Pile of Foundation Pit under Vertical Load

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Abstract. In order to explore the side deformation of the retaining piles of the foundation pit under vertical load and the sensitivity analysis of influencing factors, based on the foundation pit of a subway station of Nanning Metro Line 5, firstly, the presence of vertical load is compared and analyzed through field monitoring data. Then use FLAC3D to establish a numerical model to verify the accuracy of the numerical model by comparing with the monitoring data, and then study the maximum displacement of each factor on the lateral pile based on the numerical model, and carry out sensitivity analysis of influencing factors through grey correlation method. The results show that: the pre-acting vertical load increases the maximum displacement of the lateral pile by 20.2%, and the position of the maximum displacement of the lateral pile is lowered by 3m, which weakens the horizontal bearing capacity of the retaining pile, but has little effect on the deformation of the lateral pile; the vertical load increases When it is 3 times larger, the maximum displacement of the lateral pile is close to the pre-warning value, and the adverse effects of the vertical load should be fully considered. The second steel support diameter can be adjusted first in the design optimization; the cohesive force and internal friction angle of the soil parameters affect the surrounding pile. The side deformation has a greater impact and should be carefully determined based on indoor tests and local engineering experience.

Keywords: Foundation pit excavation; Vertical load; Field monitoring; Numerical simulation; Grey correlation method.

1. Introduction

With the rapid development of urban construction, a large number of subway station deep foundation pit engineering arises at the historic moment [1-4]. In recent years, foundation pit safety accidents occur frequently, lateral deformation of foundation pit retaining pile has become one of the focus issues in engineering. Lateral deformation of retaining pile of foundation pit is affected by horizontal excavation unloading, it is also usually affected by external loads, such as heap unloading load, vehicle dynamic load, explosion impact load and so on.

Domestic scholars Lin Gang et al. [5] used finite element software to find that lateral displacement of retaining structure under unbalanced pile load on both sides of foundation pit shows opposite variation rule. Yao Aijun et al. [6] studied the deformation of foundation pit retaining structure under asymmetric load through on-site monitoring data, The conclusions obtained are consistent with the research results of Lin Gang et al. [5]; Li Tao et al. [7] analyzed the influence of vertical pile load size and pile load distance on lateral deformation of retaining pile through model test, when the vertical pile load increases, the pile lateral displacement goes through three stages of initial, rapid and slow growth; Yang Ligong et al. [8] used ABUQUS to simulate the impact of explosion impact load on the deformation of foundation pit at different excavation depths; Hu et al. [9] used first-order reliability theory to evaluate the safety of envelope structure under train load, and discussed the influence of many factors on the stability of the envelope; Le Jinchao et al. [10] found through numerical analysis that the closer the moving traffic load is to the retaining pile, the greater the displacement of the retaining pile is, and it increases with the increase of load frequency; Xu et al. [11] analyzed the impact of vehicle load on the foundation pit retaining system by using the elastic

foundation beam method and three-dimensional finite element method, and provided appropriate reinforcement schemes; Wang et al. [12] found in their study that the deformation of foundation pit retaining structure under bias load is quite different from that of ordinary foundation pit retaining structure, and has different influences on the surrounding environment and buildings; Jin Yabing et al. [13] studied the stress deformation of envelope structure under five types of asymmetric load from the perspective of theoretical analysis and applied it in engineering examples. The above domestic and foreign scholars have conducted in-depth discussion on the deformation of foundation pit retaining structure under various loads, but few scholars have studied the lateral deformation law of foundation pit retaining pile under vertical load in actual engineering and the sensitivity of influencing factors. Therefore, it is of great practical significance to study the lateral deformation law and the sensitivity of influencing factors of the retaining pile of foundation pit under vertical load.

In this paper, based on the foundation pit project of a subway station in Nanning Metro Line 5, the lateral deformation law of the foundation pit retaining pile with or without vertical load is compared and analyzed by on-site monitoring data. Then, the finite difference software FLAC3D is used to establish numerical simulation and verify the accuracy of the numerical model by comparing with the monitoring data. Then, the influence of various factors on the maximum lateral displacement of pile is studied based on the verified numerical calculation model, and the sensitivity analysis of the influencing factors is carried out, which can provide design and construction optimization suggestions for similar projects.

2. Engineering background

This paper relies on the foundation pit project of a subway station of Nanning Metro Line 5. The length of this foundation pit of subway station is 594.4 m, the width of standard section is 19.2 m and the excavation depth is 16 m. The main enclosure structure of the station adopts the structural system of bored perfusion enclosure pile internal support and rotary jet grouting between piles. Enclosure pile diameter 1.2 m, pile length 22 m. The horizontal spacing of adjacent internal supports is 9 m, and three vertical internal supports are set. The first one is 800×900 mm meter type reinforced concrete support, located at the depth of the foundation pit 0.5 m. The diameter of the second and third steel supports are 800 mm and 609 mm, with wall thickness of 16mm, located at the depth of the foundation pit 6.4 m and 11.9 m respectively. The plan diagram of foundation pit is shown in Fig. 1.

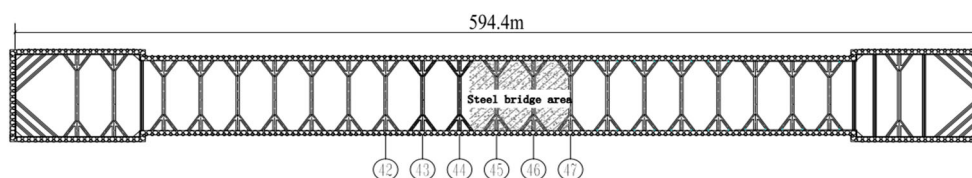


Figure 1. Schematic diagram of the foundation pit.

In order to ensure the normal travel of the surrounding residents and the normal operation of the bus station, before the excavation of the foundation pit, the passage steel bridge was built in the range of 44-47 axis. The transverse passage width of the steel bridge was 25.5 m meters, and the longitudinal span was 21.2 m. The steel bridge is made of berley beam splice, with 0.25 m thick concrete driving panel laid above, and the vertical load of about 1.05×10^4 kN is transmitted downward to both sides of the retaining piles through steel supports. Before the excavation of the foundation pit, the vertical load of the Bridge has been applied to the retaining pile. With the excavation and unloading of the foundation pit soil, the retaining pile is subjected to the horizontal load, and the displacement and deformation occur under the vertical and horizontal combined load. The cross-section of the standard section of the envelope subjected to vertical and horizontal combined loads is shown in Fig 2.

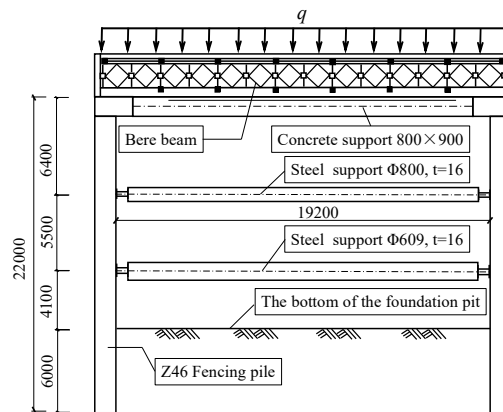


Figure 2. Sectional view of retaining structure of foundation pit under vertical load.

3. Data analysis of lateral deformation detection of retaining piles

Lateral displacement of retaining pile is one of the important bases to judge the stability of foundation pit. The lateral displacement of retaining pile of foundation pit was monitored by inclinometer, and the variation rule of lateral displacement of retaining pile under vertical load was analyzed by comparing the monitoring data. Role in advance vertical load range is 44 ~ 47 axis, with 42 shaft not lateral displacement of the retaining pile under vertical load as a comparison, and monitoring the excavation and support within the following 0.5 m and the lateral displacement of pile bottom, draw the lateral displacement of the retaining piles contrast diagram as shown in Fig 3.

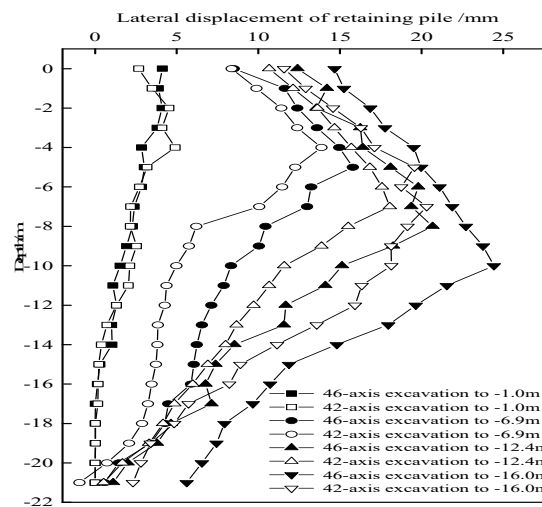


Figure 3. Comparison diagram of pile lateral displacement with and without vertical load.

It can be seen from Fig.3 that regardless of whether a vertical load is applied, the lateral deformation of the pile is basically the same, with the increase of excavation depth, the lateral deformation changes to the shape of 'small at both ends and large in the middle'. Therefore, the vertical load applied in advance has little influence on the deformation form of the retaining pile. Regardless of whether a vertical load is applied, the lateral displacement of the pile increases with the increase of the excavation depth; When the excavation is shallow, the displacement difference between the two is small. When the excavation is completed, the maximum lateral displacement of the pile with vertical load is 24.4 mm, and the maximum displacement of the pile without vertical load is 20.3 mm. The pre-acted vertical load makes the pile side The maximum displacement increased by 20.2%, and the position of the maximum lateral displacement of the pile also decreased by 3m, which is about 18.8% of the excavation depth, indicating that the pre-acted vertical load

increases the lateral displacement of the pile and weakens the horizontal bearing capacity of the retaining pile, the designers should fully consider the adverse effect of vertical load and limit the excessive lateral displacement of the pile. In addition, when the excavation reaches -6.9 m, the lateral displacement of the pile increases significantly, and the frequency of pit monitoring at this stage should be strengthened to avoid pit safety risks.

4. Numerical simulation and analysis of influencing factors

4.1 Calculation model and parameters

Numerical simulation of foundation pit excavation and support is carried out based on the finite difference software FLAC3D. In order to improve the calculation efficiency, according to the symmetry calculation principle, 1/2 of the actual project is selected for modeling. The influence range of the foundation pit excavation [14] is about 4 to 5 times the depth of the excavation. The size of the calculated model is determined to be 155m×180m×80m, the soil is simulated by the solid element of the Mohr-Coulomb constitutive model, and the internal support is simulated by the beam structural element. The grid division is based on the foundation pit center, gradually thinning from near to far, with a total of 104,260 units and 111,321 nodes, and the 1/2 foundation pit calculation model is shown in Fig 4.

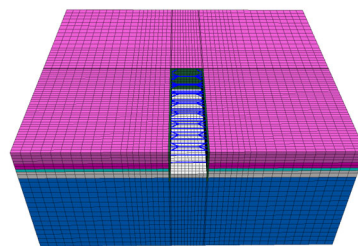


Figure 4. Calculation model of 1/2 foundation pit.

The force form of the bored retaining row piles is similar to that of the underground continuous wall. According to the principle of equivalent stiffness, it is converted into the thickness H of the simulated ground connection wall through formula (1). The physical and mechanical parameters of the retaining structure are shown in Table 1.

$$H = 0.838D \sqrt[3]{1/(1+t/D)} \quad (1)$$

Where, H is the equivalent wall thickness, t is the spacing between adjacent piles, and D is the diameter of bored pile.

Table 1. Physico mechanical properties of retaining structures.

| Retaining structure | Elastic modulus/GPa | Poisson's ratio | Density/(kg·m) ⁻³ |
|----------------------|---------------------|-----------------|------------------------------|
| Bored retaining pile | 31.5 | 0.2 | 2500 |
| Concrete support | 30.0 | 0.2 | 2500 |
| Steel support | 200.0 | 0.3 | 7980 |

4.2 Numerical model verification

Based on the FLAC3D numerical calculation model established above, the 42-axis and 46-axis lateral displacements of the retaining piles under the condition of working condition 5 are calculated, and compared with the pile lateral displacement monitoring data for verification, the drawing is shown in Fig. 5.

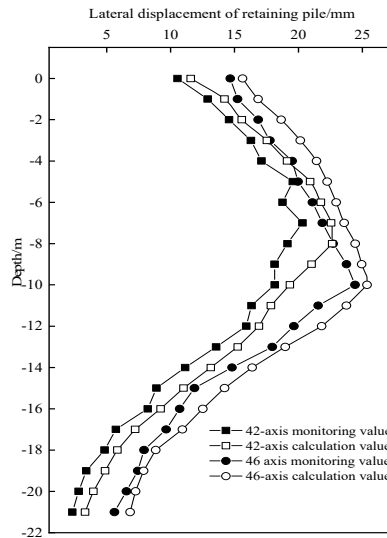


Figure 5. Comparison between measured and calculated values of lateral displacement of pile in working condition 5.

As shown in Fig. 5, the pile lateral displacement and monitoring data obtained by numerical calculation are in good agreement, and the two pile lateral deformation laws also tend to be basically the same. Specifically, the difference of maximum lateral displacement of pile without vertical load is 2.3mm, and that of maximum lateral displacement of pile with vertical load is 1.0mm, both of which are small, indicating that the numerical calculation model and parameter values are reasonable and can effectively simulate the lateral deformation of retaining pile under vertical load.

Meanwhile, from the numerical calculation results in Figure 5, the maximum lateral displacement of the pile under vertical load is 25.4 mm, and that of pile without vertical load is 22.6 mm. The maximum lateral displacement of pile under pre-acted load increases by 2.8 mm, which is consistent with the law shown in the monitoring data, thus verifying that the pre-acting vertical load will increase the lateral displacement of the pile and weaken the horizontal bearing capacity of the retaining pile.

4.3 Analysis of influencing factors of pile lateral displacement

4.3.1 Influence of vertical load size

Based on the above validation of numerical model, and on the basis of the other external conditions, the total design of 6 different vertical load on pile top beneath cap size, respectively is the size of the original vertical load 0.5 times, 1.0 times and 1.5 times, 2.0 times, 2.5 times, 3.0 times, in different under the vertical load of pile lateral displacement as control index, the largest point as shown in fig. 6.

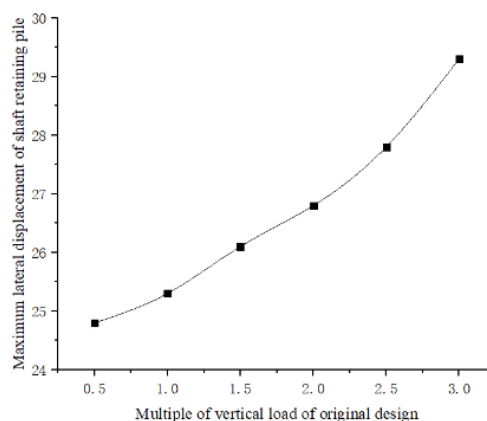


Figure 6. Maximum lateral displacement of retaining piles under different vertical loads.

It can be seen from Fig. 6 that the maximum lateral displacement curve of the pile shows an increasing power function with the increase of the Pre-effect vertical load in the range of 0.5 ~3.0 times. In the range of 0.5~1.5 times vertical load, the maximum lateral displacement of the pile changes gently and the slope of the curve is small. The vertical load in this range has little effect on the maximum lateral displacement of the pile. In the range of 1.5~3.0 times of vertical load, the slope of the lateral maximum displacement curve of the pile is getting larger and larger, and the influence of the Pre-effect vertical load on the lateral maximum displacement of the pile is becoming more and more obvious. Specifically, the maximum lateral displacement of the pile under 3.0 times vertical load is 29.6 mm, which is close to the early warning value of 30 mm. In the range of 0.5 ~ 3.0 times of vertical load, the variation amplitude of the maximum lateral displacement of the pile is 4.8 mm, which is about 18.9 % of the maximum lateral displacement of the original design pile. The Pre-effect vertical load has a great influence on the maximum lateral displacement of the pile. Designers should fully consider the adverse effects of the size of the vertical load to ensure the safety and stability of the foundation pit.

4.3.2 Influence of embedded depth of retaining piles

Keep other conditions unchanged, a total of six different embedded depth supporting scheme, the corresponding embedded depth are 4 m, 6 m (original design), 8 m, 10 m, 12 m, 14 m, drawing six different embedded depth scheme of pile lateral maximum displacement curve, as shown in Fig. 7.

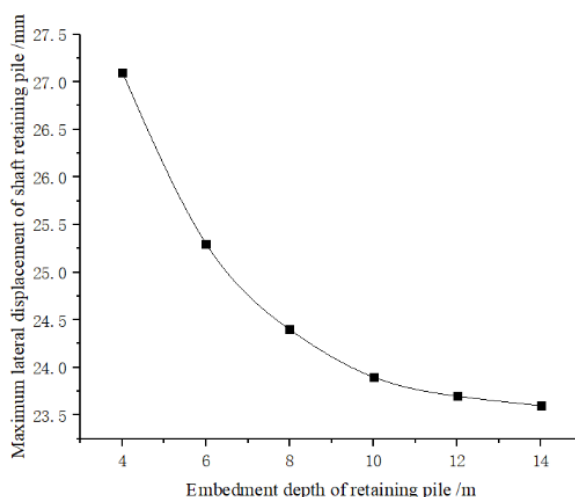


Figure 7. Maximum lateral displacement of retaining piles under different embedded depths.

It can be seen from Fig. 7 that the lateral maximum displacement of retaining piles under vertical load is negatively correlated with the embedded depth. The original design embedded depth is 6 m. When the embedded depth is reduced to 4 m, the maximum lateral displacement of the pile increases by 1.7 mm, the slope of the curve is steep, and the change rate is fast. When the embedded depth of the retaining pile increases by 2 m on the basis of the original design, the reduction rate of the maximum lateral displacement of the pile decreases gradually, and the curve tends to be flat. When the embedded depth increases to 14 m, the corresponding maximum lateral displacement of the pile is 23.4 mm, which is only 2 mm smaller than the maximum lateral displacement of the pile under the original design embedded depth. It shows that in such practical engineering design, the embedded depth of the retaining pile cannot be blindly increased to reduce the lateral displacement of the pile, and the economy of the project cost should be comprehensively considered. Through the numerical calculation and analysis in this section, it is known that the maximum lateral displacement of piles does not exceed the monitoring and early warning value of 30 mm in the range of 4 ~ 14 m embedded depth. The original design of embedded depth comprehensively considers the safety and economy of foundation pit, and the design is reasonable.

5. Sensitivity analysis of influence factors of pile lateral displacement

Using the grey correlation method to analyze the factors influencing the sensitivity of lateral displacement of the pile, retaining pile lateral displacement of the largest selection of 46 axis as the reference sequence, the corresponding matrix of the X, the system of comparative sequence Y by vertical load size, retaining pile embedded depth, the diameter of the second passage for support, in the name of the second wall thickness and parameters soil cohesive force, internal friction Angle of soil parameters such as composition. Except for vertical load, the influence of other factors on the reference sequence is negatively correlated, which requires reciprocal processing. Finally, the mean value method is processed by means of dimensionless data of the reference matrix X and comparison matrix Z, and the new matrices X' and Z' are obtained as follows:

$$X' = \begin{bmatrix} X'_1 \\ X'_2 \\ X'_3 \\ X'_4 \\ X'_5 \\ X'_6 \end{bmatrix} = \begin{bmatrix} 0.923 & 0.945 & 0.975 & 1.008 & 1.049 & 1.101 \\ 1.098 & 1.029 & 0.997 & 0.972 & 0.956 & 0.948 \\ 1.038 & 1.035 & 1.024 & 1.001 & 0.971 & 0.930 \\ 1.067 & 1.033 & 1.002 & 0.983 & 0.967 & 0.948 \\ 1.169 & 1.084 & 1.010 & 0.952 & 0.913 & 0.871 \\ 1.156 & 1.083 & 1.006 & 0.959 & 0.917 & 0.878 \end{bmatrix}$$

$$Z' = \begin{bmatrix} Z'_1 \\ Z'_2 \\ Z'_3 \\ Z'_4 \\ Z'_5 \\ Z'_6 \end{bmatrix} = \begin{bmatrix} 0.286 & 0.571 & 0.857 & 1.143 & 1.429 & 1.714 \\ 1.883 & 1.256 & 0.942 & 0.753 & 0.628 & 0.538 \\ 1.166 & 1.149 & 1.111 & 1.000 & 0.875 & 0.700 \\ 1.358 & 1.164 & 1.018 & 0.905 & 0.815 & 0.741 \\ 1.277 & 1.135 & 1.022 & 0.929 & 0.851 & 0.786 \\ 1.277 & 1.135 & 1.022 & 0.929 & 0.851 & 0.786 \end{bmatrix}$$

The difference matrix N is obtained by subtracting the absolute values of the matrices X' and Z'.

$$N = \begin{bmatrix} N_1 \\ N_2 \\ N_3 \\ N_4 \\ N_5 \\ N_6 \end{bmatrix} = \begin{bmatrix} 0.637 & 0.373 & 0.117 & 0.135 & 0.380 & 0.613 \\ 0.786 & 0.227 & 0.055 & 0.219 & 0.328 & 0.410 \\ 0.128 & 0.114 & 0.087 & 0.002 & 0.097 & 0.231 \\ 0.290 & 0.131 & 0.016 & 0.078 & 0.153 & 0.208 \\ 0.108 & 0.051 & 0.011 & 0.023 & 0.062 & 0.085 \\ 0.121 & 0.042 & 0.015 & 0.031 & 0.066 & 0.093 \end{bmatrix}$$

The maximum value and minimum value of difference matrix N are nmax and nmin respectively, and the correlation coefficient matrix is obtained by using Equation (2) as follows.

$$\xi_j(i) = \frac{n_{\min} + \rho n_{\max}}{n_j(i) + \rho n_{\max}} \quad (i, j=1,2,\dots,6) \tag{2}$$

In the formula, ρ is the resolution coefficient, usually 0.5.

$$\xi = \begin{bmatrix} \xi_1 \\ \xi_2 \\ \xi_3 \\ \xi_4 \\ \xi_5 \\ \xi_6 \end{bmatrix} = \begin{bmatrix} 0.384 & 0.515 & 0.774 & 0.748 & 0.511 & 0.393 \\ 0.335 & 0.637 & 0.882 & 0.645 & 0.548 & 0.492 \\ 0.758 & 0.779 & 0.823 & 1.001 & 0.807 & 0.633 \\ 0.578 & 0.754 & 0.966 & 0.839 & 0.724 & 0.658 \\ 0.788 & 0.890 & 0.978 & 0.949 & 0.868 & 0.826 \\ 0.768 & 0.908 & 0.968 & 0.932 & 0.861 & 0.813 \end{bmatrix}$$

The correlation coefficient matrix γ is obtained by equation (3) as follows:

$$\gamma_j = \frac{1}{n} \sum_{i=1}^n \xi_j(i) \quad (i, j=1,2,\dots,6 \quad n=6) \tag{3}$$

$$\gamma = \begin{bmatrix} \gamma_1 \\ \gamma_2 \\ \gamma_3 \\ \gamma_4 \\ \gamma_5 \\ \gamma_6 \end{bmatrix} = \begin{bmatrix} \text{Vertical load size} \\ \text{Maintenance pile embedded depth} \\ \text{Diameter of the second steel support} \\ \text{Thickness of the second steel supporting steel pipe} \\ \text{Soil parameter cohesion} \\ \text{Soil parameter internal friction angle} \end{bmatrix} = \begin{bmatrix} 0.554 \\ 0.590 \\ 0.800 \\ 0.753 \\ 0.883 \\ 0.875 \end{bmatrix}$$

The calculated correlation value is in the range of 0~1. When the value is closer to 1, the stronger the correlation between the influencing factors and the maximum lateral displacement of the pile, the greater the influence on the maximum lateral displacement of the pile. On the contrary, when the value is closer to 0, the influence of influencing factors on the lateral maximum displacement of pile is smaller. The order of correlation degree calculation results in the above formula is $\gamma_5 > \gamma_6 > \gamma_3 > \gamma_4 > \gamma_2 > \gamma_1$ from large to small. The corresponding correlation degree ranking of influencing factors is soil parameter cohesion, soil parameter internal friction Angle, diameter of the second steel support, wall thickness of the second steel support, embedment depth of retaining pile and vertical load. For foundation pit retaining pile under vertical load, the natural geological cohesive force and Angle of internal friction of soil conditions have the biggest impact on the lateral displacement of the pile, that at the beginning of the project construction of geological prospecting work, the determination of soil parameters is very important, should give full consideration to the appropriate accurate test method and local experience in engineering design. Among the design factors, the order of influence on the maximum lateral displacement of the retaining pile under vertical load is the diameter of the second steel support, the wall thickness of the second steel support and the embedded depth of the retaining pile. When the design optimization needs to control the maximum lateral displacement of the retaining pile, the diameter of the second steel brace can be adjusted with priority. The influence of vertical load on the maximum lateral displacement of the retaining pile is the only positive correlation among the six factors. In this kind of foundation pit design condition, the vertical load is the key factor to be considered and the design safety reserve should be improved.

6. Conclusions

The numerical calculation results are in good agreement with the monitoring data, and the numerical model and parameter values are reasonable. Both results show that the vertical load in advance has little influence on the lateral deformation form of the retaining pile.

Under the vertical load of 0.5~3.0 times of the original design, the maximum lateral displacement curve of pile presents an increasing power function form, with a variation amplitude of 4.8mm, about 18.9% of the maximum lateral displacement of the original design. Under the vertical load of 3.0 times, the maximum lateral displacement of pile is close to the warning value, and the vertical load has a great influence on the maximum lateral displacement of pile.

When the cohesion force and internal friction Angle change in the range of 0.8 to 1.3 times, the corresponding maximum lateral displacement amplitude of pile is 29.5% and 27.6% of the maximum lateral displacement of the original design pile, respectively. Both of them have a great influence on the maximum lateral displacement of the retaining pile under vertical load. On the basis of the original design of embedded depth, reducing the embedded depth has great influence on the maximum lateral displacement of the retaining pile, and the original design of embedded depth is reasonable.

According to grey correlation theory, the correlation degree of six factors is calculated as follows: soil parameter cohesion, soil parameter internal friction Angle, diameter of second steel support, wall thickness of second steel support, embedment depth of retaining pile and vertical load. Among the negative correlation factors, soil parameters have the greatest influence on the maximum lateral displacement of the pile, while the vertical load has the only positive correlation on the maximum lateral displacement of the retaining pile. Therefore, the vertical load is the key factor that needs to be considered to improve the design safety reserve.

Acknowledgments

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