Study on Lateral Bearing Capacity of Cantilever Rigid Piles under Large Horizontal Displacement

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Abstract. In order to analyze the lateral ultimate bearing capacity of cantilever rigid pile with large horizontal displacement, this paper studies the distribution characteristics of soil resistance on the side of pile and the calculation method of lateral bearing capacity of pile foundation by means of numerical simulation and theory. The results show that under the condition of large displacement, the soil in front of the pile is yielded layer by layer from top to bottom, and when the soil layer on the side of the pile reaches the limit displacement, the soil resistance on the side of the pile no longer increases with the increase of displacement. The lateral ultimate bearing capacity of cantilever rigid pile under large horizontal displacement is fitted and calculated by using the ultimate displacement of pile side soil, in which the fitting effect of modified “m” method is the best, and the applicable range of foundation coefficient distribution needs to be further studied.

1. Introduction

Compared with other basic types, the pile foundation has the advantages of good seismic performance, high bearing capacity and small settlement. Therefore, pile foundation is the most widely used foundation in the current infrastructure industry, such as rectangular anti-slide pile and bridge pier pile foundation in landslide control. At present, there are a lot of studies on the bearing capacity of piles under horizontal load [1-6], but less studies on the lateral ultimate bearing capacity of rigid cantilever piles under large displacement. Because the current code of bridge pile foundation only allows a small amount of horizontal displacement at the top of the pile [7-8], in fact, for the anti-slide pile in the slope and the pile-plate retaining wall in the roadbed fill, it only needs to meet the normal function of the superstructure, and there is no strict restriction on the horizontal displacement of the pile top.

Shen Zhujiang [9] pointed out that the ultimate design of anti-slide pile should include the minimum anti-slide force required for landslide stability, the ultimate anti-slide force generated by pile to soil, and the ultimate bearing capacity of anti-slide pile itself without failure. However, the calculation of the ultimate bearing capacity of anti-slide pile was not deeply analyzed. Xu he [10], Wu Feng [11], Lao Weikang [12] respectively calculated the foundation coefficient according to the static load test of pile foundation in situ, and analyzed the law of foundation coefficient changing with displacement and the problem of m value in the case of large displacement. However, the foundation coefficient is reduced empirically only under the elastic theory, and the inelastic characteristics of the soil on the side of the pile under large displacement are not taken into account. Cui xinzhuang et al. [13] comprehensively analyzed the failure mode, displacement rule and ultimate bearing capacity of rigid pile under lateral load through model test, theoretical derivation and numerical simulation, etc. However, the size of the
model pile is small (the maximum diameter is 7.6cm), and the simulated object is the highway guardrail column. The obtained results have certain applicable conditions.

In China, there are few studies on the elastic-plastic characteristics of the lateral soil of rigid pile under large displacement and its influence on the lateral ultimate bearing capacity. In order to solve the above problems, the failure mode and ultimate bearing capacity of rigid pile under lateral load are studied by numerical simulation, and some of the soil on the side of pile has entered the plastic yield state under the condition of large displacement. This paper presents a calculation method of lateral earth resistance on piles of rigid pile under large displacement is put forward, and the load-displacement curve of pile foundation is obtained, which provides a theoretical basis for determining the transverse ultimate bearing capacity of rigid pile.

2. Numerical simulation

2.1. Model establishment

2.1.1. Numerical model establishment

In this paper, the finite element software MIDAS GTS NX is used to establish the three-dimensional solid numerical calculation model, as shown in figure 1. The overall model simulates the actual working condition according to the proportion of 1/10. The soil layer is 1.5m long and 1.5m wide, with a total of three layers. The thickness of each layer is 0.5m. The rectangular pile in the model is 2m long, 0.2m×0.3m in section size, 1.3m in depth, and 0.2m from the bottom of the pile to the boundary of soil layer.

In order to fully reflect the mutual stress and deformation between the model pile and the soil, the corresponding steel bar of the rigid pile body adopts the disjunctive 1D implantable beam element. As shown in figure 2, in order to reasonably simulate the large displacement at the top of the pile, a non-tensile strength interface element with a thickness of zero is set at the pile-soil section behind the pile, allowing pile-soil separation to occur when the pile body has a large lateral displacement. The total number of units is 78274. The model is surrounded by normal displacement constraints (front and rear Y 0, left and right X 0), and the bottom is X, Y, Z displacement constraints (X=Y=Z=0).

2.1.2. Parameter value

The material parameters of the pile-soil separated interface element in the model are calculated automatically by using the interface assistant tool in MIDAS GTS to input the virtual thickness coefficient (tv) and the strength reduction coefficient (R). According to the stiffness and nonlinear parameters of adjacent elements, virtual thickness coefficient and strength reduction coefficient.
structural member and relative stiffness difference of foundation, the stiffness and parameters of different interface materials are obtained. The general value range of $t_v$ is $0.01 \pm 0.1$. The larger the strength difference between geotechnical and structural members is, the smaller the input value is. The value of 0.01 is selected in this paper. The strength reduction coefficients of general structural members and adjacent soil are as follows: ① cohesion less soil / steel = 0.6~0.7, ② clay / steel = 0.5, ③ cohesion less soil / concrete = 0.8~1.0, ④ clay / concrete = 0.7~1.0. In this paper, the strength reduction coefficient $R$ is 0.8.

The soil adopts more-coulomb constitutive method (ideal elastic-plastic). Since the static calculation of MIDAS finite element software (without considering the permeability) has little influence on the result when the pore ratio is not involved in the calculation, it is set as the system default value 0.5. Both concrete and steel bar adopt elastic constitutive structure. The specific parameters are shown in Table 1.

| Soil layer | Heavy degree $\gamma$ (kN·m$^{-3}$) | Cohesion $c$ (kPa) | Internal friction angle $\psi$ (°) | Compression modulus $E_c$ (MPa) | Elastic modulus $E_s$ (MPa) | Poisson's ratio $\mu$ |
|------------|------------------------------------|-------------------|----------------------------------|-------------------------------|--------------------------|-----------------------|
| Soil①     | 19.7                               | 15                | 14                               | 9                             | -                        | 0.3                   |
| Soil②     | 19.8                               | 16                | 15                               | 9                             | -                        | 0.3                   |
| Soil③     | 20.8                               | 16                | 16                               | 10                            | -                        | 0.3                   |
| Concrete   | 25                                 | -                 | -                                | 18300                         | 0.3                      |
| Steel bar  | 78                                 |                   | 200000                           | 0.3                           |                          |

2.1.3. Design of numerical test scheme

This paper mainly studies the elastic-plastic characteristics of the soil on the side of rigid pile under large displacement and its influence on the transverse ultimate bearing capacity, so the graded displacement load (2mm-68mm) is applied at the top of the pile. The variation law of soil resistance and horizontal displacement at different depth is analyzed in order to explore its influence on the lateral bearing capacity of pile foundation.

2.2. Numerical simulation results

In order to analyze the yield failure of soil layer on the side of pile with large displacement at pile top, the variation curve of soil resistance with pile top load at different depth is analyzed, as shown in figure 3. In the picture, 0m corresponds to the ground, -0.1m is the pile 0.8m, and so on.

With the increase of displacement load, the soil resistance at different depth of pile side increases linearly at the beginning, and finally tends to the level, and the laws are basically similar. The greater the depth is, the smaller the soil resistance value is when the displacement load is small in the early stage. This shows that under the horizontal load, that is, the shallow soil first plays a role under the large displacement, from the elastic stage to the plastic stage. With the gradual increase of load, the deep soil begins to play a role, and the soil resistance increases.
Considering the different displacements of the pile under the same load and at different depths, in order to analyze the relationship between the ultimate soil resistance and the lateral displacement of the pile at different depths, the relationship between the displacement of each section and the soil resistance of the pile is plotted, as shown in figure 4. As shown in figure 4, with the increase of lateral displacement, the soil resistance on the side of the pile increases approximately linearly at first, then gradually yields to the inflection point and finally showed a “near level”. The greater the depth of the section, the greater the displacement load when the soil yield, indicating that with the increase of the depth and the increase of the stress level in the soil, the strength of the soil becomes greater and greater, that is, the shallow pile side soil yield first under the condition of lateral large displacement.

3. Calculation of ultimate bearing capacity

In order to show the ultimate bearing capacity of pile side soil at different depths, the lateral displacement of pile side soil yield at each depth is regarded as the ultimate displacement at this depth, and the limit displacement diagram of pile side soil shown in figure 5 is obtained. From figure 5, it can be seen that the ultimate displacement of soil on the side of pile increases approximately linearly under different depth. The fitting curve $y = 28.59x - 16.57$ is obtained by linear fitting in Origin software, and the correlation coefficient is $R^2 = 0.9965$. In the formula, $y$ represents the limit displacement and $x$ is the position of the section.

According to the m method [8] in Appendix Q of Code for Design of Highway Bridge and culvert Foundation and culvert (JTGD63-2007), the ultimate displacement is used as the criterion to calculate the transverse ultimate bearing capacity of rigid cantilever pile under the condition of large displacement. When the lateral displacement of the soil on the side of the pile exceeds the limit displacement at this depth, the soil resistance is calculated according to the limit value, that is, it is considered that the displacement increment after yield does not produce the increment of soil resistance. This is consistent with the law that the strain increases infinitely and the stress does not increase after yield in the ideal elastic-plastic constitutive model. For the specific calculation formula, see formula (1):

$$P = \sum_{i=1}^{n} C_{x_i} b_i \delta$$

In the formula: $C$ is the foundation coefficient, when the value is taken by m method, it is $C = m z_i$; $z_i$ is the value of section depth; $x_i$ is the value of lateral displacement at the section; $b_i$ is the calculated width of the pile, where the rectangular single row pile is $b_1 = 0.3$ according to the code; $\delta$ is the calculated thickness at the section ($\delta = 0.1$);
The above formula uses the displacement of the central section to represent the average displacement of the upper and lower spacing piles, calculated by segments, and finally summed up. Because the lateral displacement of rigid pile is linear distribution, it can be considered that the simplified calculation is reasonable.

![Figure 5. Limit displacement diagram of pile side soil.](image)

Fig. 6. shows the load-displacement curve (load-displacement) diagram calculated under different lateral foundation coefficient distribution. Among them, the "modified m method" is calculated by the relevant formula in reference [2] (m=12000, c_0=10000), and the "c method" is calculated according to the relevant formula in reference [14] (c_0= 25000).

As can be seen from figure 6, the load-displacement curve of the modified m method has a good fit with the numerical simulation results both in terms of the variation law and the limit value. It shows that it is applicable to use the ultimate displacement of pile side soil to calculate the ultimate bearing capacity of rigid pile in the case of large displacement, but the applicable range of foundation coefficient needs to be further studied.

4. Conclusion

In this paper, the lateral ultimate bearing capacity of rigid piles under large displacement is studied by numerical simulation and theoretical methods. The following conclusions are drawn:

1. With the increase of transverse load, the failure of rigid pile shows that the soil in front of the pile yielded layer by layer, and the plastic zone began to expand to the depth after the shallow soil reached the ultimate load.

2. By using the limit displacement of pile side soil, the nonlinear solution of pile side limit soil resistance based on elastic foundation beam theory is realized. As a result, the load-displacement curve of the pile foundation in the whole process and the theoretical bearing capacity of the rigid pile when the displacement of the pile foundation on the ground is greater than 6mm are obtained.

3. In different distribution of foundation coefficient, the modified m method has a good fit with the numerical simulation results, which shows that it is applicable to calculate the ultimate bearing capacity of rigid pile under the condition of large displacement by using the ultimate displacement of soil on the side of pile.

4. In this paper, the applicable range of foundation coefficient calculation needs to be verified by practical engineering, and further research is needed.

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