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Non-linear Calculation and Analysis on Horizontal Bearing Pile

Jun Yao*, Ya Wang

Department of Architectural Engineering, HeFei University, HeFei, AnHui, China
yaojunaaa@qq.com

At present, numerical methods are mainly used in the calculation and consideration on lateral displacement of horizontal bearing pile under the non-linear relation of pile side soil mass, while the analytical methods are relatively seldom used. Based on the constitutive relation between Winkler foundation model and D–P model, this article deduces on the pile under the horizontal load in the layered soil to reach the calculation formula for maximum horizontal displacement, bending moment and loading of the pile shaft. Meanwhile, ANSYS software is used to re-calculate the calculation model and compare the calculations from the formula with numerical results. It is indicated by the analysis that the analytical results are similar to numerical results. The formula may be used to simplify the calculation of lateral displacement of horizontal bearing pile in engineering.

1. Introduction

In recent years, vertical piles with horizontal bearing are widely used in port and bridge engineering. However, related theoretical research on horizontal bearing pile is not complete. In port and shipping engineering, horizontal bearing piles not only bear vertical loads, but also bear horizontal loads such as ship breasting force and wave force, resulting in relatively complicated force scenario. It has been made clear in the horizontal load test of the pile that in case of small displacement, horizontal load value and horizontal displacement are in non-linear relation. With the further increase of the horizontal displacement, the soil mass around the pile fails by yield. Conventionally, finite element numerical calculation is mainly used in the calculation on the pile, however, many constitutive models are idealized elastic-plastic models having certain defects that result in the fact that the non-linear and plastic yield of the soil mass cannot be considered sufficiently, which leads to insufficient accuracy of the calculation results. Conventional m method cannot consider the plastic yield of the soil mass around the pile, while for D–P curve method(He, 2008) , although it takes the non-linear and plastic yield characteristics of the soil mass into consideration, its result is obtained mainly through the experiment, therefore it is difficult to be used widely without necessary experiment data(Xia, 2010) . Based on the above consideration, more and more people begin to use analytical calculation which is more comprehensive to research the non-linear characteristics of horizontal bearing single pile.
Horizontal displacement analytic calculation of horizontal bearing single pile mainly through the establishment of the model spring mechanics , and push the pile horizontal displacement of the formula by the way of mathematical calculations. In the process of derivation, it should think through the force condition of the single pile and establish the differential equations by the foundation of force balance of single pile .It also need certain mathematical methods and boundary conditions of displacement to get the formula expression ultimately.

2. Analytical method

2.1 Basic assumptions

1) The pile shaft dives into the soil mass for enough depth, namely semi-infinite pile with the pile diameter R, pile length L, elastic modulus EI. The top of the pile is free end without constraint and the pile top horizontal load is F and bending moment is M;
2) The elastic modulus of the soil mass EI increases with the depth in a linear way;

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3) The soil counterforce P and pile displacement Y is of linear relation. With the increase of Y, the limit of soil counterforce will be reached.

2.2 Calculation formula

Based on the above assumption, create pile-soil calculation model to obtain differential equation for the horizontal displacement curve of pile shaft:

$$EI\frac{\mathrm{d}^4 u}{dz^4}+ku=0 \tag{1}$$

Where: EI is elastic modulus of pile shaft; U is horizontal displacement of pile shaft; Z is depth underneath the ground surface; $k=k_0 d$ where k_0 is counterforce coefficient of foundation and R is pile diameter.

It has been made clear from the pile shaft experiment that the soil mass around the pile shaft has entered the plastic phase even when relatively small displacement occur at the pile shaft and the elastic process is very short, therefore, the plastic yield of the soil mass must be taken into consideration in order to precisely calculate the displacement of the pile shaft. This article uses soil mass constitutive relation proposed by Bowles(1977) as shown in the figure 1. This constitutive relation is widely used in the calculation of horizontal bearing pile(Wang, 2004).

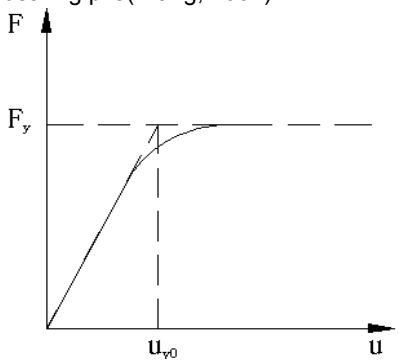

Figure 1: Soil mass constitutive relation

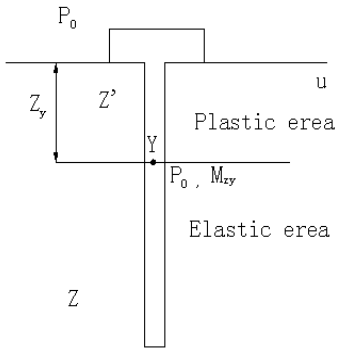

Figure 2: Single pile calculation model

In order to facilitate the formula calculation, establish single pile horizontal model as shown in the figure 2, wherein Y is the demarcation point between elasticity and plasticity of the soil mass, which can be achieved from force equilibrium of the pile shaft in this model:

$$Q=-P+P_y Z^{/} \tag{2}$$

$$M=-PZ^{/}+0.5P_y Z^{/2} \tag{3}$$

$$\varphi=\frac{PZ^{/2}}{2EI}-\frac{P_y Z^{/3}}{6EI}-\frac{M_t Z^{/}}{EI} \tag{4}$$

$$U = \frac{PZ^{/3}}{6EI} - \frac{P_y Z^{/4}}{24EI} + \frac{M_t Z^{/2}}{2EI} + C_1 Z^{/} + C_2 \tag{5}$$

Where: Q– shear force of pile shaft, M – the bending moment of pile shaft, φ- turn angle of pile shaft, u– the displacement of pile shaft, *P*– the horizontal load of pile shaft, M_t- the bending moment of the single pile top.
In formula (5), the paper can obtained the value of C_1 and C_2 according to boundary conditions, when Z=0, we can get C_1=C_2=0. Therefore calculation formula for horizontal displacement of single pile U can be obtained:

$$U = \frac{PZ^{/3}}{6EI} - \frac{P_y Z^{/4}}{24EI} + \frac{M_t Z^{/2}}{2EI} \tag{6}$$

The single pile U is the horizontal displacement of single pile as shown in the figure 3. The calculation formula for horizontal displacement of pile top can be obtained through differential equation for horizontal displacement curve of pile shaft. This formula takes plastic yield of soil mass into consideration, improving the accuracy of calculation.

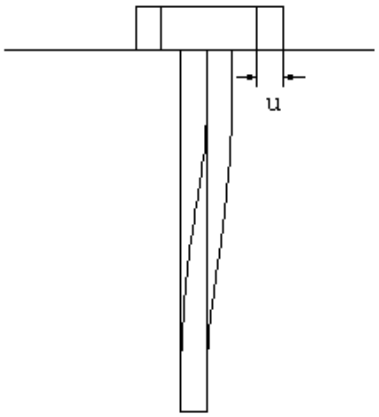

Figure 3： Schematic diagram of Horizontal displacement of single pile

3. Finite element calculation

3.1 Basic assumptions

(1) In actual engineering, the single pile is of reinforced concrete material. Since the concrete and the reinforcing steel bar are different materials, contact unit shall be set up between the steel bar and the concrete during setting the calculation model. However, this article mainly considers the relation between single pile and soil, in addition, the contact surfaces between the steel bar and the concrete are in large number, leading to heavy workload, therefore, the contact relation between the steel bar and the concrete is not to be considered and only certain rigidity is applied to the pile to represent the bending resistance natural of the reinforced concrete.
(2) In actual engineering, usually pile cap structure is provided at the upper part of the pile top, which is equivalent to set rigid constraint to the pile top to reinforce the bending resistant rigidity of the pile shaft. However, this article does not include pile cap in order to display the maximum horizontal displacement of the single pile top.
(3) Because of the special geographical situation of near-shore projects，Water stress, seepage force and the earth stress must bring about some influence on the relation of pile-soil. And these influence are very complex and difficult to summarize the law, at the same time this effect is relatively small. Therefore, this article ignores this effect of pile.
(4) One of the features of this article is that the soil is divided into some layers according to the actual project situation. However, not every layer of the soil is homogeneous which contain some magazines of different ingredients. Therefore, in order to simplify the finite element model, each layer of soil is treated as homogeneous strata in this paper which can simplify the calculation process and does not affect the calculation results.
This article uses finite element software ANSYS12.0 to analyze the single pile foundation structure. The software has a built-in Drucker-Prage model which is an idealized elastoplastic model, this model can describe

the coordinated non-linear deformation of the foundation soil against the single pile foundation under the horizontal load, this model suit to analyze this relationship of pile-soil, reflecting the pile-soil interaction (Yao, 2013).

The formula of stress in DP constitutive model:

$$\sigma_e = e\beta\sigma_m + \left[\frac{1}{2}\{S\}^T[M]\{S\}\right]^{\frac{1}{2}} \tag{7}$$

3.2 Modeling

(1) The part of soil mass is established in layers in accordance with actual working condition, and then corresponding parameters are set up according to mechanical properties of the soil mass for every layer of soil mass model to ensure reliability. The complete model which reflects the different layers is shown in Figure 6;

(2) For the pile shaft, corresponding parameters are set up as per the strength grade of reinforced concrete, and the network of the pile shaft is divided according to grid width of the soil mass, this meshing way improve the accuracy of calculation of model(Zhao, 2008);

(3) Two different materials of the soil mass and the pile are connected to each other sufficiently through setting up surface to surface contact unit for the pile shaft and the soil mass to ensure the continual transmission of stress and strain. Contact pairs are shown in Figure 7(Yao, 2012);

(4) After establishing the model for the single pile and the soil mass, and dividing the grid, load and calculate as per actual working condition to obtain calculation results. Stress nephograms of the soil mass and the pile shaft are shown in Figure 4 and 5.

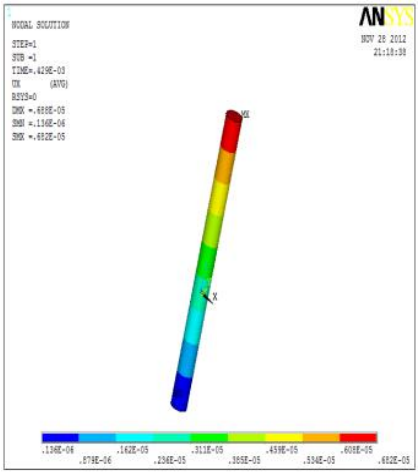

Figure 4: Stress nephogram of single pile

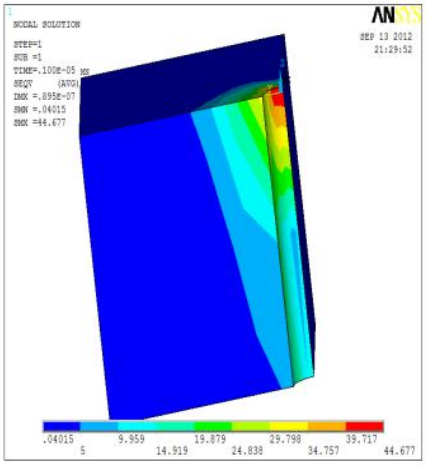

Figure 5: Stress nephogram of soil

Figure 6: Single pile-soil mass model

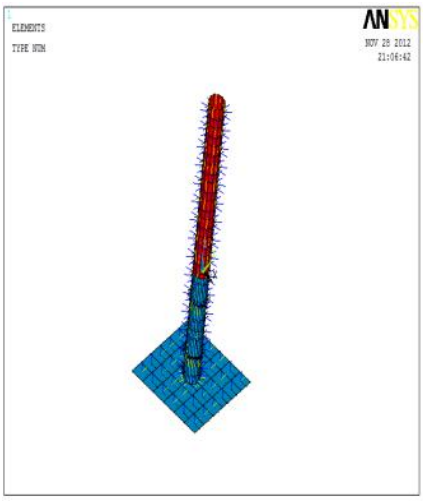

Figure 7: Single pile-soul mass contact pair

4. Calculation example analysis

Long piles are used in the temporary dock of Quanzhou Port. These long piles are affected by the upper load of the dock, wave force from the sea and ship breasting force. The pile shaft is jointly affected by horizontal load and vertical load. This article calculates the horizontal displacement of the pile shaft through on-site geological exploration data on the temporary dock of Quanzhou Port and pile shaft data to verify the accuracy of the formula calculation results. Meanwhile, use finite element software to carry out the numerical calculation under the same working condition and compare the two calculation results. See Table 3.1 for the specific working condition of soil mass layering at the temporary dock of Quanzhou Port which come from the data of geological exploration.

According to soil parameters and mechanical parameters provided by Table 3.1, Table 3.2, the paper establish the finite element model of single pile and soil according to the method described above 3.2 and make numerical calculation. At the same time taking these parameters into the equation (6), and then calculate.

Table 1: Geophysical parameters of dock in Quan Zhou Port

Layer No.	Layer name	Layer thickness (m)	Elastic modulus (MPa)	Poisson's ratio	Internal friction angle (degree)	Cohesion (KPa)
①	Sludge, fine sand layer	3.9	3.8	0.36	11.9	12.5
②	Residual soil layer	14.5	6.5	0.36	13.1	14.6
③	Intensely weathered granite layer	19.5	8.6	0.36	13.4	18.5

In order to reflect the accuracy of the calculation, this article provides multiple sets of mechanical parameters. Use finite element software ANSYS12.0 and analytical formula to calculate horizontal displacement of the pile shaft under different horizontal loads in accordance with the actual working condition at the temporary dock of Quan zhou Port. See Table 2 for the results and see Figure 8 for the comparison between the calculation results. Figure 8 show the different result under the different calculation methods, the main difference lies in the different calculation algorithms, which is also the view of a new calculation proposed by this paper.

Table 2: Numerical calculation result and formula calculation result under the same working condition and their comparison

Pile diameter (mm)	Horizontal load F (KN)	ANSYS calculation result (mm)	Formula calculation result (mm)	Deviation (%)
1000	100	24.1	27.2	12.8%
1000	200	25.9	30.1	16.2%
1000	300	26.7	31.1	16.8%
1000	400	27.8	34.5	13.6%

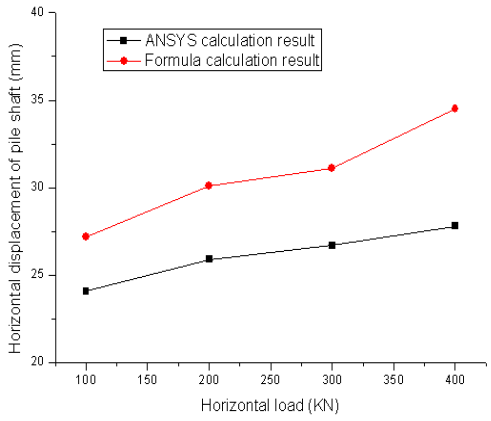

Figure 8: Comparison between formula calculation result and ANSYS calculation result

5. Conclusion

Through the two different calculations, this paper get different results. And get the following conclusions after a process of comparative analysis:

(1) Under the same working condition, analytical formula calculation result is basically consistent with the numerical calculation result with the deviation less than 20%, representing the accuracy and reliability of the formula calculation. However, difference does exist in calculation results due to different calculating mechanism.

(2) Compared with the corresponding numerical calculation result, the result of the formula calculation is relatively less, mainly due to the consideration of plastic yield of the soil mass, mutual interaction between pile and soil, and the suppression to the deflection of the pile against further increase before the yield of soil mass. This outcome confirms the accuracy of the derivation formula in this article, representing the pile-soil interactive mechanism more accurately.

(3) Compared with numerical calculation, the formula calculation is simpler and its result is more reliable. In actual engineering, the application is more convenient and can simplify the calculation process. Therefore, formula calculation is superior over numerical calculation in a certain extent.

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