Research On Rigid Cap Thickness Of Pile Foundation For Overhead Transmission Line Cap

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Abstract. One of the basic assumptions in the calculation and design of the internal force of cap pile is the rigid cap. The current national standard and standard only require the structure of cap thickness but not the stiffness. With the increase of the number of piles and the width of caps, the pile foundation of overhead transmission line can not meet the requirements of rigid caps only according to the structural requirements, which is unsafe for cap design. In this paper, the calculation method of rigid cap thickness is derived theoretically, and the Midas finite element method is used for numerical simulation. The requirement of rigid cap thickness is obtained by analyzing the deformation of cap and the change law of pile top reaction, and the theoretical calculation formula is compared and verified. The research results of this paper provide some basis and help for the theoretical analysis of rigid cap and the design of cap pile.

Keywords: Cap Pile; Rigid cap ; Theoretical analysis; Finite element

1 INTRODUCTION

Pile cap is an important component that supports the superstructure and transmits the load of the superstructure to the foundation. According to "Research on Load Analysis and Optimal Design of Overhead transmission line cap pile", it is known that the common design calculation methods of cap pile internal force include "simple calculation method", "equal generation frame method" and "cap - pile - soil" synergistic calculation method. These calculation methods have a basic assumption: rigid cap assumption, that is, the cap deformation is linear and small under the combined action of external load and pile top internal force. In the engineering design, the thickness of a cap is assumed first, the internal force of each pile is calculated according to the rigid cap, and then the bearing capacity of the cap under bending, shearing and punching is checked.

However, due to the wide width of the cap, the required bearing thickness is generally very small to meet the requirements of bending, shearing and punching bearing

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capacity. According to the structural requirements, the minimum thickness of the cap required by the "Technical Code for Building Pile Foundation " [5] should not be less than 300mm, the "Technical Code for Design of Foundation of Overhead Transmission line " [6]and "Variable stiffness design technology of rigid cap pile foundation for onshore wind turbines. Electric Power Survey and Design " [2] stipulates that the cap thickness should be 1~2 times of the pile diameter, and should not be less than 300mm.

Overhead transmission line cap piles commonly include four pile caps, six pile caps and nine pile caps. With the increase of load and the new structural types such as narrow base towers, the number of cap piles may reach 16 pile, 25 pile or even 36 pile. The width of cap plates is relatively large, while the stiffness of cap is relatively small. Therefore, it is not clear whether the cap designed only according to the current design concept and construction requirements meets the cap rigidity assumption.

For multi-pile cap, the thickness of the cap is generally small only according to the bearing capacity of bending, shear and punching. If the rigidity assumption of the cap is not met, the internal force of the pile foundation calculated is not accurate, and it is unsafe for engineering design. Therefore, it is necessary to scientifically study the calculation principle of the thickness of multi-pile cap meeting the rigidity requirements. Wang Jun,Zhou Liang[1]、Kim Xueyang[3]、Chen Zhuchang[8] 、 Hain S J [10]in the literature that the rigid caps need to be further studied and determined

In the paper " Research on mechanical characteristics of pile group foundation thick cap ", Sun Yanhui[4] et al proposed that the overall stiffness of pile raft foundation can be determined by the following formula:

$$K = \frac{E_R H^3 \delta_P}{12(1-\nu_R^2)s\sqrt{A_R}} \qquad (1)$$

Flexible state, K⩽0.01; Elastic state, 0.01<K<1; Rigid state, 1⩽K<10; Absolute rigidity, K⩾10.

Dong Jianguo[7] approximated the relative stiffness formula of pile-raft foundation in the book Foundation of High-rise Building-Co-action heory and Practice as:

$$K = \frac{E_R H^3 \delta_P}{12(1-\nu_R^2)sB_R} \qquad (2)$$

The current industry regulations refer to the " Strut-and tie models for the design of pile caps " mentioned in the book PERRY A[9] proposed to meet the conditions of absolute rigidity:

$$\frac{6E_0 I_0}{\rho_1 S^3} > \left(\frac{n}{1.5}\right)^4 \qquad (3)$$

Through the comprehensive analysis of the above literatures, it can be seen that the larger the cap thickness is, the smaller the vertical bearing stiffness of the simulated pile is, and the stronger the load spreading ability of the cap plate is. It is very important to design pile group foundation of iron tower how to request cap thickness according to rigidity.

2 THEORETICAL SOLUTION OF RIGID CAP

2.1 Derivation of Basic Formula

In the pile-cap system, a row of piles is taken in the plane, as shown in Figure 1, and the cap is simplified into a continuous beam supported on the elastic fulcrum. The elastic coefficient of the elastic fulcrum is the axial stiffness of the pile. There is a certain difference in the stress state of the elastic supported continuous beam in the rigid and non-rigid state, as shown in Figure 2, and this difference is the basis for establishing the criterion of cap stiffness.

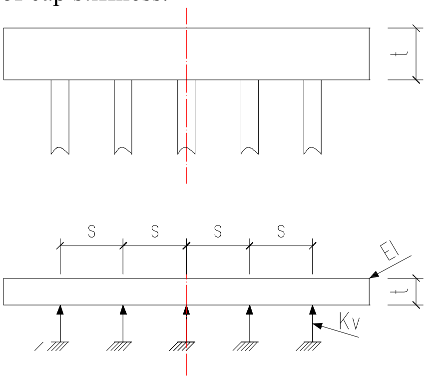


Fig. 1. Simplified illustration of pile-cap

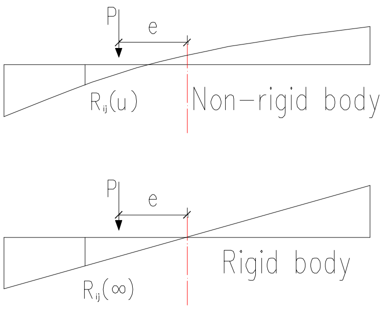


Fig. 2. Stress state of rigid beam and flexible beam

2.2 Non-rigid Beam

For a non-rigid beam with elastic support, the fulcrum reaction V can be obtained from the five-moment equation:

$$\mu M_{i-2}+(1-\mu)M_{i-1}+(4+6\mu)M_i+(1-4\mu)M_{i+1}+\mu M_{i+2}=-\mu l(V_{i-1}^0-2V_i^0+V_{i+1}^0) \qquad (4)$$

Under the action of external load, the fulcrum reaction force Vi can be obtained by the following formula:

$$V_i=V_i^0+(M_{i-1}-2M_i+M_{i+1})/L \qquad (5)$$

According to the above calculation process, the reaction force of each fulcrum of the continuous beam with elastic support under the action of load can be obtained.

2.3 Rigid Beam

For the case of rigid continuous beams, the calculation method can translate the concentrated load P to the section centroid according to the translation principle of force in rigid body mechanics, and replace it with a vertical force P acting on the section centroid O and an eccentricity Pe acting on the rigid beam. the vertical load on any fulcrum i is

$$V_i = P / n \pm Pex_i / \sum x_i^2 \qquad (6)$$

2.4 Rigid Cap Thickness Calculation Method

It is assumed that there is a load P acting on any point j of the beam. Under rigid and non-rigid conditions, the reaction force generated by beam j at point i is V_{ij1} and V_{ij2}. When $V_{ij1}=V_{ij2}$, the cap can be regarded as a rigid body. According to the above principle, the pile with different column numbers is analyzed and calculated. If the error between the elastic calculation result and the complete rigidity is not more than 10% as the standard of rigidity treatment, the relationship between u and n can be shown as follows:

$$u > (n/1.4)^4$$
$$u = 6EI / (\rho_1 S^3) \qquad (7)$$

The calculation formula of cap thickness which can be treated according to rigidity is:

$$t > \sqrt[3]{\frac{0.521 n^4 \rho_1 s^3}{Ea}} \qquad (8)$$

3 THEORETICAL CALCULATION OF CAP THICKNESS OF OVERHEAD TRANSMISSION LINE

In this section, four piles, nine piles and sixteen piles commonly used in overhead transmission line cap piles are used as reference for calculation, typical geology of Jiangsu Province is used as design basis, and different pile lengths and diameters are used as variables to calculate different cap thicknesses, which can provide reference for design calculation and finite element analysis. The theoretical calculation results of rigid cap thickness under different parameters are shown in Table 1

Table 1. List of theoretical calculated thicknesses of rigid caps

Number	Fundamental force	Pile parameter	Rigid cap thickness(m)
1	N=5000kN	n=9， D=1	1.64

		s=3m， l=25m	
2	N=5000kN	*n*=9， *D*=0.8 s=3m， l=25m	1.54
3	N=5000kN	*n*=9， *D*=1.2 s=3m， l=20m	1.76
4	N=5000kN	*n*=4， *D*=1 s=3m， l=25m	0.96

Note: n is the number of piles, D is the pile diameter, s is the pile distance, l is the pile length. c=20kpa, ψ=5, r=18kN/m3, m=5000kN/m4.

4 FINITE ELEMENT SIMULATION OF CAP PILE

According to the analysis in the above section, it can be seen that the rigid cap thickness is different with different pile number, pile diameter and pile length. In this chapter, by using numerical simulation method, pile foundation under different pile number, pile length and stress is selected. By changing cap thickness, the internal force distribution and settlement law of cap pile are studied, and the accuracy of the calculation theory of rigid cap thickness is verified.

4.1 Model Building

The geotechnical finite element analysis software Midas GTS NX was used to establish the whole three-dimensional finite element model for calculation and analysis. The coordinate system of the calculation model is Cartesian coordinate system, and the coordinate origin (0,0,0) is set at the southwest corner of the model surface.

4.2 Parameter Setting

The structural part of the model is assumed to be in the elastic stage, so the structure is simulated by linear elastic constitutive model. The pile foundation was simulated by 1D unit, and the other structural components were simulated by 3D unit. The model structure is made of C30 concrete with a weight of 26kN/m3, elastic modulus Es is 3×107kN/m2, Poisson's ratio v is 0.3. The established model is shown in Figure 3.

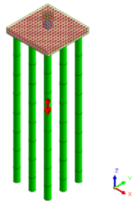


Fig. 3. General situation of typical cap pile model

4.3 Parameter Setting

(1) the soil layer is homogeneous and isotropic, and the deformation and stress of the structure are within the elastic range.

(2) The interaction between the structure and the soil is simulated by the contact surface simulation method, and the mechanical behavior of the soil and the related structure is simulated by the strength reduction method of the structural surface material.

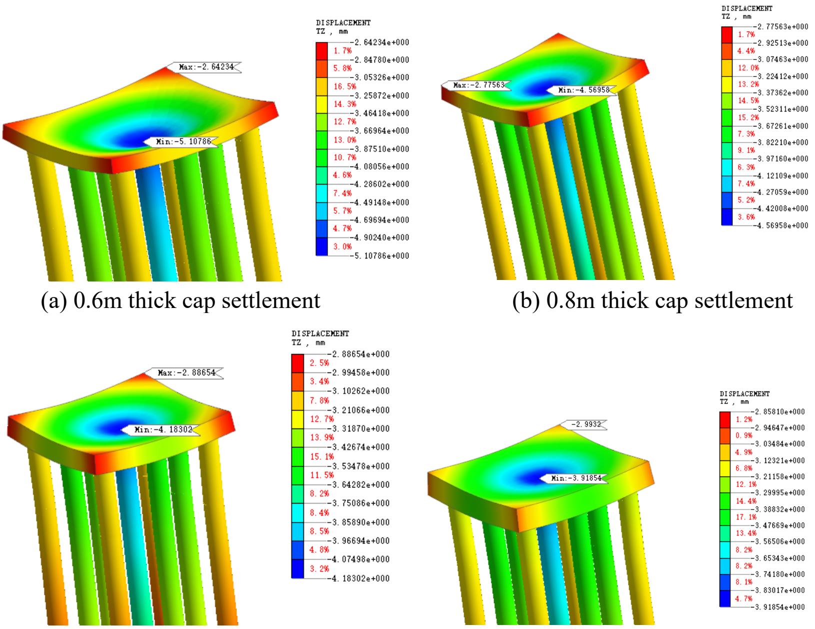
(3) The model is surrounded by a fixed water head boundary, the upper and lower surface of the model are impervious boundaries, and the flow rate is zero.

(4) The theoretical derivation in this paper is suggested to be carried out when the bearing properties are the same and the influence of groundwater is not considered. Therefore, the assumptions of the finite element model are consistent with the theoretical derivation.

4.4 Model Result

4.4.1 9 Piles, Pile Diameter D=1m, Pile Length h=25m, F=5000kN, Cap Thickness 0.6~1.8m

(1) Settlement result



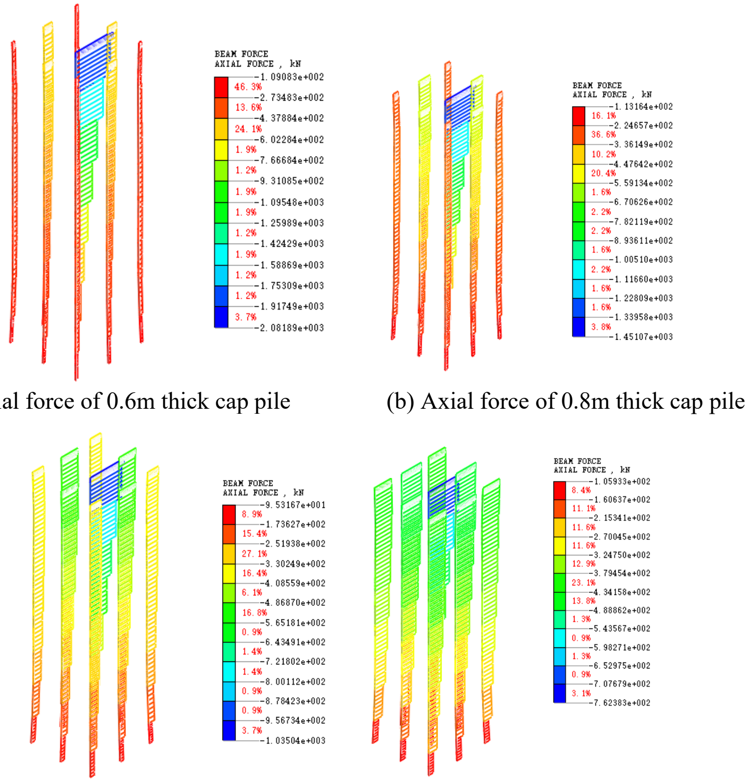
(a) 0.6m thick cap settlement (b) 0.8m thick cap settlement

(c) 1.0m thick cap settlement (d) 1.2m thick cap settlement

Fig. 4. Soil settlement and settlement cloud of No. 1 cap

As shown in Figure 4, the soil settlement of No. 1 cap pile is centered on the surface of load application and expands to all sides. The center settlement is the largest and the surrounding settlement is the smallest, which conforms to the general law of soil settlement change. The maximum soil settlement ranges from 3.7mm-5.2mm, and decreases with the increase of cap thickness. The settlement of cap is centered on the surface of load application and expands to all sides. The center settlement is the largest and the surrounding settlement is the smallest, which accords with the general law of settlement change of cap pile. The maximum settlement range of cap is 3.6mm-5.1mm, and with the increase of cap thickness, the maximum settlement of cap gradually decreases, and the difference between the maximum settlement and the minimum settlement of cap pile gradually decreases.

(2) Results of axial force on top of pile



(a) Axial force of 0.6m thick cap pile (b) Axial force of 0.8m thick cap pile

(c) Axial force of 1.0m thick cap pile (d) Axial force of 1.2m thick cap pile

Fig. 5. Cloud diagram of pile axial force distribution of No. 1 cap pile

As shown in Figure 5, the axial force development trend of pile foundation is that the vertical downward direction of the cap approximately exhibits a parabolic trend of decline, and the numerical size of each pile foundation is different due to the different pile positions, which conforms to the general law. With the increase of cap thickness, the axial force distribution of pile tip gradually changes from the original maximum to the axial force of each pile.

(3) center line settlement of cap and pile top axial force of No.1 cap pile

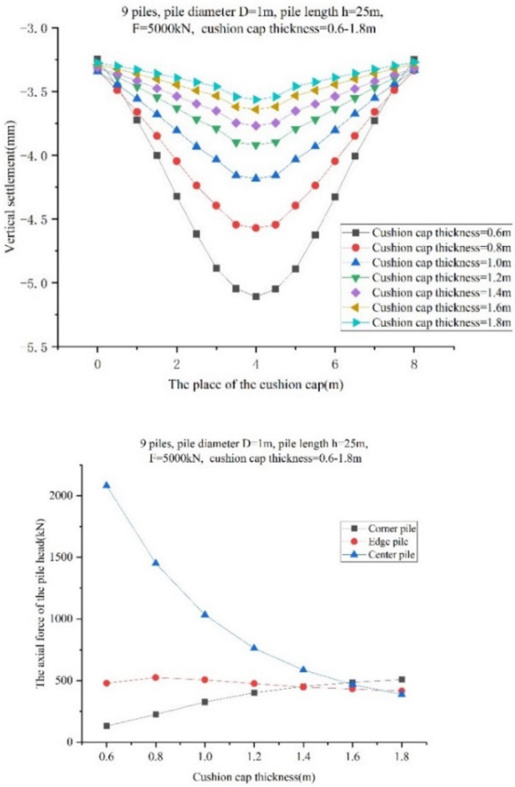
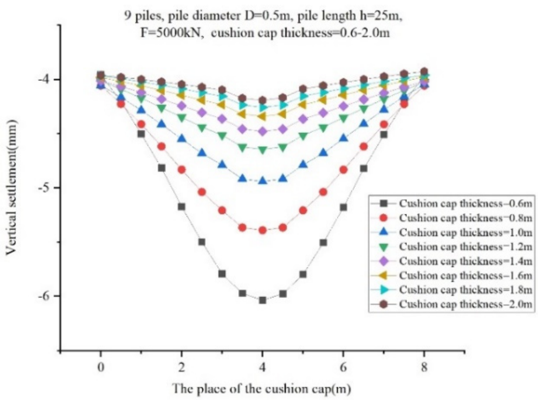


Fig. 6. Settlement curve of center line and pile top axial force

4.4.2 9 Piles, Pile Diameter D=0.8, Pile Length h=25, F=5000kN, Cap Thickness 0.6~2.0m



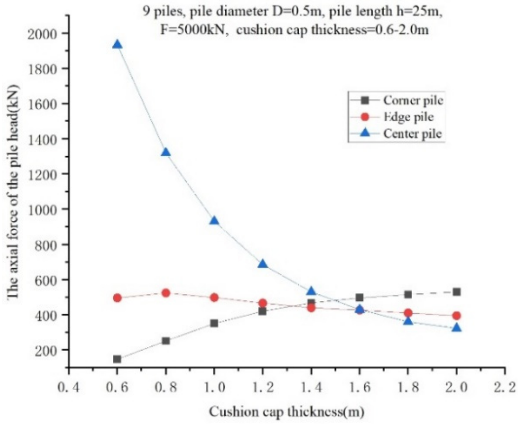


Fig. 7. Settlement curve of center line and pile top axial force of No.2 cap pile

4.4.3 9 Piles, Pile Diameter D=1.2m, Pile Length h=20m, F=5000kN, Cap Thickness 0.6~2.0m

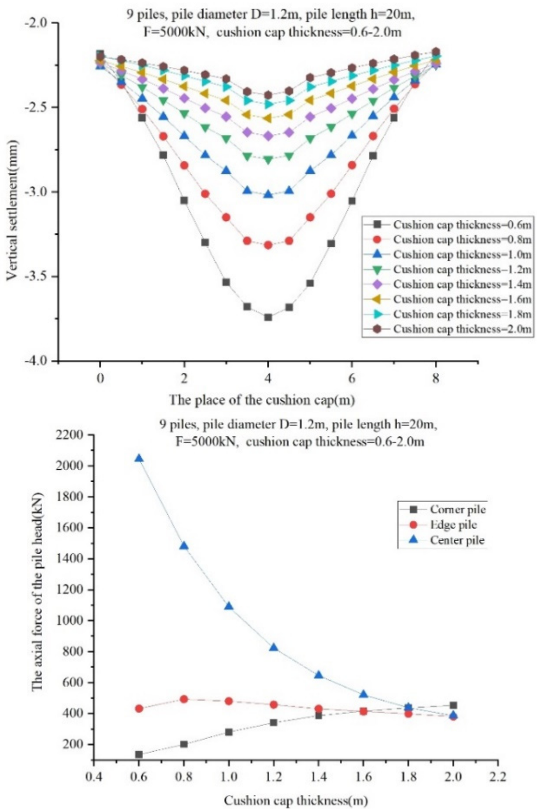
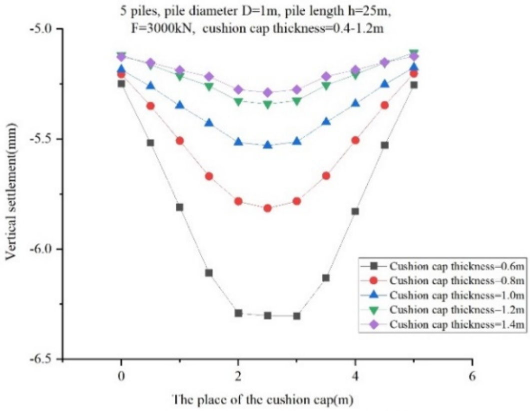


Fig. 8. Settlement curve of center line and pile top axial force of No.3 cap pile

4.4.4 5 Piles, Pile Diameter D=1, Pile Length h=25, F=3000kN, Cap Thickness 0.4~1.2m



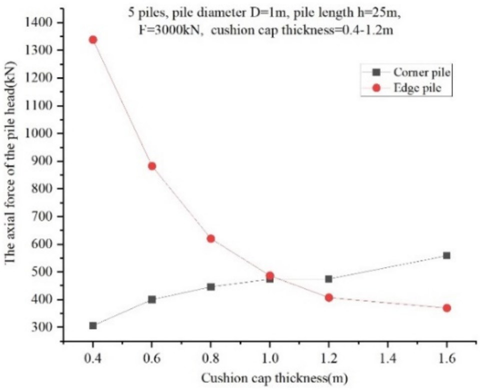


Fig. 9. Settlement curve of center line and pile top axial force of No.5 cap pile

As shown in Fig 6~ Fig 9, the settlement distribution of the center line of the cap is inverted U-shaped, and the variation curvature has a relatively obvious change near the pile position. With the increase of cap thickness, the settlement value of each point is gradually reduced, the settlement distribution is gradually uniform, and the change rate is gradually reduced.

with the increase of cap thickness, the axial force of the center pile gradually decreases, that of the side pile gradually decreases after a brief increase, that of the corner pile gradually increases, the axial force of each pile tends to be equal, and the change rate of the axial force of each pile gradually decreases. When the cap is 1.6m, the axial force distribution of each pile is approximately equal.

4.5 Comparison Between Numerical Simulation Results and Theoretical Values

the numerical simulation results are in line with the general rule. Table 2 shows the cap thickness of each cap pile when the axial force value of each pile tends to be equal with the calculation theory, and the difference is small. The theoretical calculation of rigid cap thickness derived in Section 2.4 has a high precision and can be used as a reference for design.

Table 2. Comparison between numerical simulation and theoretical values of rigid cap thickness

Number	Number of piles	Pile diameter(m)	pile length(m)	load(kN)	Rigid cap thickness(m)	Modeling cap thickness (m)
1	9	1	25	5000	1.64	1.6
2	9	0.8	25	5000	1.51	1.5
3	9	1.2	25	5000	1.76	1.8
4	4	1	25	3000	0.96	1

5 CONCLUSIONS AND SUGGESTIONS

This paper intends to analyze the rigid cap theory of cap pile and obtain the theoretical calculation method of the thickness of rigid cap pile. According to the common pile layout types of cap pile of overhead transmission line, the theoretical rigid cap pile thickness of cap pile with different pile number, pile length and pile diameter is calculated. In addition, the geotechnical finite element analysis software Midas GTS NX was used to establish the overall three-dimensional finite element model, and the required thickness of rigid cap was analyzed and verified by the deformation of cap and the pile tip reaction. The main conclusions and suggestions are as follows:

(1)It is not clear whether the cap designed according to the design concept and structural requirements of cap according to "Technical code for design of foundation of overhead transmission line" and "Technical code for building pile foundations" meet the assumption of cap rigidity. According to the current analysis, the thickness and structural thickness required to meet the bending, shearing and punching resistance of cap are only applicable to caps with fewer piles(The number of piles is less than 4, and the width of the cap is less than 5m).t is not applicable to caps with more piles.

(2)The calculation method of rigid cap thickness is derived through theoretical analysis, and Midas modeling is used to verify the results. The results show that: 1) Regardless of the distribution form of external load on the cap surface, the maximum axial force on the top of the pile always appears at a specific pile position; 2) When the cap is thin, the cap settlement is centered on the loading surface and expands to all sides. The center settlement is the largest and the surrounding is the smallest. The axial force on the top of the center pile is the largest, the corner pile is the smallest, and the side pile is the second. 3) With the increase of cap thickness, the above differences gradually decrease, and the settlement of cap and the axial force of pile tip tend to be uniform.

(3) Midas modeling is used to analyze and verify the required thickness of rigid cap through cap deformation and pile tip reaction. It is recommended that the theoretical calculation results and the finite element results have a large coincidence, and the theoretical calculation can provide a basis for design.

(4) In view of the load bearing characteristics of the overhead power transmission industry foundation, For more than 4 piles or a cap width greater than 5m, it is suggested to verify the cap stiffness according to the theoretical analysis results in this paper, and appropriately increase the cap thickness to improve the design safety and reliability.

(5) The derived formula in this paper is based on a single soil layer (soil layer is homogeneous and isotropic). For soil with different soil properties or anisotropy, the theoretical formula needs to be further modified.

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