Study on the optimization of pile group foundation under oblique load

Bin Dong¹*, Liang Wang², Wenting Liu³, Aiguo Han³, Yang Tang¹, Lei Yuan²

¹ State Grid Sichuan Electric Power Company, Chengdu, Sichuan 6100411, China
² State Grid Aba Power Supply Company, Maoxian, Sichuan 624000, China
³ Chengdu University of Technology, Chengdu, Sichuan 610059, China

*Corresponding author e-mail: 785769632@qq.com

Abstract. With the development of economy and science and technology in China, pile group foundation is widely used in various constructions to meet the complex engineering conditions. Pile foundation is often affected by inclined load (i.e. horizontal load and vertical load). The behavior of pile under inclined load is much more complex than that under single load. In engineering, the vertical component and the horizontal component of the pile top are often calculated separately, and then modified. This method is only suitable for small deformation, which is different from the actual situation. In this paper, taking the four pile foundation as an example, through the rotation of the cushion cap (the column does not rotate) and the column eccentricity, the force of the foundation pile can be relatively uniform. At the same time, the design calculation of the group pile foundation under the oblique load can be approximately equivalent to the design calculation of the group pile foundation under the single vertical load. When the force distribution on the pile top is relatively uniform under the same inclined load, the eccentricity of the column has a linear relationship with the depth of the cap. Through ABAQUS numerical simulation analysis, the correctness of the above understanding is verified.

1. Introduction

With the development of economy and science and technology in China, pile group foundation is widely used in various constructions to meet the complex engineering conditions. Pile foundation is often affected by inclined load (i.e. horizontal load and vertical load). The behavior of pile under inclined load is much more complex than that under single load. In engineering, the vertical component and the horizontal component of the pile top are often calculated separately, and then modified. This method is only suitable for small deformation, which is different from the actual situation.

In order to study the bearing characteristics of pile foundation under oblique load, experts and scholars at home and abroad have carried out many researches. Zhao Minghua et al. studied the bearing characteristics of pile foundation under oblique load through numerical simulation and test methods[1-3]; Chari et al. studied the bearing mechanism of pile foundation under oblique load through tests[4-5]; Meyerhof studied the distribution of soil pressure on the side of pile under eccentric inclined load in homogeneous sandy soil, homogeneous clay and layered soil through indoor model test, and obtained the calculation formula of ultimate bearing capacity of pile under certain
assumptions[6-7]; Huang Jin et al. studied the displacement and stress characteristics of pile groups under inclined loads of different sizes and obliquity through ABAQUS[8].

In this paper, the influence of the horizontal component of the inclined load on the pile group is properly simplified and offset, and how to make the axial force of piles tend to be uniform is studied. The design calculation of the pile group foundation under the inclined load is approximately equivalent to the design calculation of the pile group foundation under the single vertical load, which simplifies the design and provides another way for the design.

Taking the "Shidaguan Chuanzhusi 220kV line project" as an example, this paper studies the factors that affect the axial pressure distribution on the top of the pile in the four pile foundation after proper treatment, reveals the factors that affect the uniformity of the pressure distribution on the top of the pile and the relationship between the factors. The research results have good reference value for the design simplification and optimization of pile group foundation under oblique load. In order to verify the correctness of the viewpoint, ABAQUS is used to carry out numerical simulation analysis of the optimized pile group foundation layout.

2. Basic ideas

With the development of economy and science and technology in China, pile group foundation is widely used in various constructions to meet the complex engineering conditions. Pile foundation is often affected by inclined load (i.e. horizontal load and vertical load). The behavior of pile under inclined load is much more complex than that under single load. In engineering, the vertical component and the horizontal component of the pile top are often calculated separately, and then modified. This method is only suitable for small deformation, which is different from the actual situation.

In order to study the bearing characteristics of pile foundation under oblique load, experts and scholars at home and abroad have carried out many researches. Zhao Minghua et al. studied the bearing characteristics of pile foundation under oblique load through numerical simulation and test methods[1-3]; Chari et al. studied the bearing mechanism of pile foundation under oblique load through tests[4-5]; Meyerhof studied the distribution of soil pressure on the side of pile under eccentric inclined load in homogeneous sandy soil, homogeneous clay and layered soil through indoor model test, and obtained the calculation formula of ultimate bearing capacity of pile under certain assumptions[6-7]; Huang Jin et al. studied the displacement and stress characteristics of pile groups under inclined loads of different sizes and obliquity through ABAQUS[8].

In this paper, the influence of the horizontal component of the inclined load on the pile group is properly simplified and offset, and how to make the axial force of piles tend to be uniform is studied. The design calculation of the pile group foundation under the inclined load is approximately equivalent to the design calculation of the pile group foundation under the single vertical load, which simplifies the design and provides another way for the design.

Taking the "Shidaguan Chuanzhusi 220kV line project" as an example, this paper studies the factors that affect the axial pressure distribution on the top of the pile in the four pile foundation after proper treatment, reveals the factors that affect the uniformity of the pressure distribution on the top of the pile and the relationship between the factors. The research results have good reference value for the design simplification and optimization of pile group foundation under oblique load. In order to verify the correctness of the viewpoint, ABAQUS is used to carry out numerical simulation analysis of the optimized pile group foundation layout.

2.1. Basic calculation formula of foundation pile stress

The inclined load transmitted from the column to the cushion cap is simplified as the force N, Nx and Ny. The piles are marked with No. 1, 2, 3 and 4 respectively, and the reaction forces on the pile top are respectively N1, N2, N3 and N4. The bearing force of soil to cushion cap is not considered, and the stress is shown in Figure 1.
Moving the external force to the center of the bottom of the cushion cap, the force calculation formula of each pile can be obtained:

\[
N_1 = \frac{N}{4} - \frac{M_x}{2l} + \frac{M_y}{2l} \tag{1}
\]

\[
N_2 = \frac{N}{4} - \frac{M_x}{2l} - \frac{M_y}{2l} \tag{2}
\]

\[
N_3 = \frac{N}{4} + \frac{M_x}{2l} + \frac{M_y}{2l} \tag{3}
\]

\[
N_4 = \frac{N}{4} + \frac{M_x}{2l} - \frac{M_y}{2l} \tag{4}
\]

1 is the distance between piles, \( M_x \) and \( M_y \) is the moment around the X and Y axis.

2.2. Ways to optimizing pile foundation stress

The vertical component of the inclined load shall be offset by a certain distance along the direction of the horizontal component (even if the column is eccentric) to offset the moment generated by the horizontal component, so as to optimize the foundation pile stress; in order to avoid the effect of the torque generated by the horizontal separation as far as possible, the cushion cap shall rotate at a certain angle (the column does not rotate), and the rotation angle should be such that one side of the cushion cap is in the same direction as the horizontal component of the inclined load. After the above treatment, it is approximately considered that the pile is only affected by axial force, and its stress is optimized to a certain extent, and the inclined load can be approximately treated as a single vertical load.

2.3. Optimization analysis of pile foundation layout

Taking the four pile foundation as an example to illustrate the optimal adjustment of the layout form. Various layout schemes are shown in Figure 3.
3. Numerical simulation research on the force of foundation pile

3.1. Basic conditions

"Shidaguan Chuanzhusi 220kV line project" is an auxiliary project for the power supply project of Chengdu Lanzhou railway. It starts from Shidaguan 220kV switching station and ends at Chuanzhusi 220kV substation. It is a double circuit line with the same tower. The total length of the line is about 2 × 107KM, and the route is roughly north-south. The route is located in Maoxian and Songpan administrative areas. The elevation of the sea level in the section where the line passes is 2600-3600m. The foundation rock and soil are mainly dense silty clay (including gravel), and the mechanical parameters are shown in Table 1.
### Table 1 Foundation rock parameter

|                         | Dense silty clay | Concrete pile |
|-------------------------|------------------|---------------|
| density                 | 1950 kg/m³       | 2500 kg/m³    |
| Young’s modulus         | 16 MPa           | 30 GPa        |
| Poisson’s ratio         | 0.34             | 0.2           |
| cohesion                | 25 kPa           |               |
| Friction angle          | 25°              |               |

#### 3.2. Simulation analysis of the stress on the top of foundation pile

The ABAQUS finite element software is used to establish the numerical simulation model. The length, width and height of the model are all 10m. Set up the column, cushion cap and pile with the pile diameter of 0.35m and length of 6m, cushion cap size of 1.8m × 1.8m × 0.6m and column size of 0.9m × 0.9m × 1.5m. The calculation model is shown in Figure 4 (taking 2 × 2 pile groups as an example). In this paper, the stress on the top of the pile is mainly studied, and the stress on the soil is not discussed. The linear elastic model is adopted for both the soil and the pile foundation.

![Numerical model](image)

External load $N=1475\text{kN}$, $N_x=202\text{kN}$, $N_y=186\text{kN}$. In order to avoid the torque caused by horizontal load as much as possible, the cushion cap rotates $45^\circ$. Four optimization schemes of pile foundation layout are simulated, which are: the buried depth of cushion cap is 0.6m, the column is not eccentric; the buried depth of cushion cap is 0.6m, the column is eccentric 0.2m; the buried depth of cushion cap is 0.9m, the column is eccentric 0.25m; the buried depth of cushion cap is 1.2m, the column is eccentric 0.3m.

#### 3.3. Analysis of numerical simulation results

Extract the stress of each node on the pile top, first calculate the average value of the stress and then multiply by the corresponding cross-sectional area to calculate the axial force of the pile top:

$$N = A \frac{1}{n} \sum_{i=1}^{n} \sigma_i,$$  (5)

$A$ is the cross-sectional area of pile top; $\sum_{i=1}^{n} \sigma_i$ is the total stress at the top of the pile; $n$ is the number of nodes at the top of the pile.

See Table 2 for the axial force on the pile top of pile group foundation under different conditions. It can be seen from the table that when the eccentricity is zero, the difference of force between each foundation pile can be more than 100kN, which is caused by the horizontal component force; when the cushion cap rotates $45^\circ$, if the eccentricity of the column is adjusted properly according to the buried depth, the bearing capacity of each foundation pile is basically the same, and the difference is kept within 30kN, which is approximately equivalent to a single vertical load, so as to achieve the purpose of optimizing the bearing capacity of the foundation pile; if the column is eccentric, the axial force of each pile is reduced by more than half, which greatly saves materials. It is worth noting that in this case, for every 0.3m increase in the buried depth of the cushion cap, the eccentricity should be increased by 5cm to keep the stress of the foundation pile relatively uniform, and the buried depth of the cushion cap is in linear relationship with the eccentricity of the column.
### Table 2 Pile stress in pile group foundation

| Buried depth/m | 0.6 | 0.6 | 0.9 | 1.2 |
|---------------|-----|-----|-----|-----|
| Column eccentricity /m | 0.2 | 0.25 | 0.3 |
| No. | Pile top axial force (kN) |
| 1<sup>o</sup> | 527.01 | 196.01 | 192.07 | 192.73 |
| 2<sup>o</sup> | 408.68 | 186.30 | 175.15 | 185.44 |
| 3<sup>o</sup> | 506.50 | 178.13 | 179.15 | 177.57 |
| 4<sup>o</sup> | 396.81 | 173.48 | 174.73 | 167.74 |

### 4. Conclusion

Through simplifying and offsetting the influence of horizontal component of inclined load on pile group, and analyzing the factors affecting the distribution of stress on pile top, combined with the stress data obtained from numerical simulation, the following conclusions are drawn:

1. The selection of cushion cap rotation angle should be based on the principle that one side of cushion cap is parallel to the direction of horizontal component of inclined load;
2. The moment caused by the horizontal load can be well offset by the eccentricity of the column, and the force of the foundation pile is relatively uniform, so the design calculation of the pile group foundation under the oblique load can be approximately equivalent to the design calculation of the pile group foundation under the single vertical load;
3. Inclined load, embedded depth of pile cap and eccentricity of column are mutually affected to optimize the force of pile group. In the design, the reasonable embedded depth of pile cap and eccentricity of column should be determined according to the relationship among the three factors;
4. Under the condition that the upper load is constant, the reasonable column eccentricity can be determined according to the load and the buried depth of bearing platform, and the reasonable column eccentricity has a linear relationship with the buried depth of bearing platform.

### References

[1] ZHAO Ming-hua, ZOU Xin-jun, ZOU Ying-sheng, et al. BEHAVIOR OF PILES UNDER INCLINED LOADS BY THE IMPROVED FINITE ELEMENT-FINITE LAYER METHOD [J]. Engineering Mechanics, 2004, 21 (3): 129 - 132. (in Chinese)

[2] ZHAO Ming-hua, HOU Yun-qiu, CAO Xi-ren. Study on the behavior of inclinedly loading pile[J]. Journal of Hunan University, 1997, 24(2): 98–109. (in Chinese)

[3] ZHAO Ming-hua, HOU Yun-qiu, SHAN Yuan-ming. Calculation and model test study on the bridge piles underinclined loads[J]. Journal of Hunan University (Natural Sciences Edition), 1999, 26(2): 86–91. (in Chinese)

[4] CHARI T R, MEYERHOF G G. Ultimate Capacity of Rigid Single Piles under Inclined Loads in Sand[J]. Canadian Geotechnical Journal, 1983, 20 (4): 849 – 954.

[5] TAIEBAT H A, CARTER J P. Numerical Studies of the Bearing Capacity of Shallow Foundations on CohesiveSoil Subjected to Combined Loading[J]. Geotechnique, 2000, 50 (4): 409 – 418.

[6] MEYERHOF G G, SASTRY V V R N. Bearing capacity of rigid piles under eccentric and inclined loads[J]. Canadian Geotechnical Journal, 1984, 21: 267 - 276.

[7] SASTRY V V R N, MEYERHOF G G. Behaviour of flexiblepiles under inclined loads[J]. Canadian Geotechnical Journal, 1990, 27: 19 – 28.

[8] HUANG Jin, WANG Guo-cai, TONG Hui-zhi. Numerical analysis of group piles works behavior under inclined loadings [J]. SHANXI ARCHITECTURE, 2011, 37 (17) : 70 - 72. (in Chinese)