Numerical Analysis of Horizontal Bearing Capacity of Composite Pile Foundation for Offshore Wind Turbine

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Abstract. In recent years, with the rapid development of offshore wind power, the installed capacity is increasing, and the traditional single pile foundation is under heavy load. Therefore, the composite pile foundation composed of single pile foundation and bucket foundation (friction wheel) installed outside the pile body is gradually adopted to ensure the safety and stability of the fan during its service. In order to study the bearing capacity of composite pile foundation, the ABAQUS finite element software is used to study the horizontal bearing capacity of composite pile foundation, analyze its bearing capacity advantages compared with the traditional single pile foundation, and further optimize the design. The results show that: under the same load, the displacement and bending moment of composite pile foundation are greatly reduced due to the existence of friction wheel, and the horizontal bearing capacity of composite pile foundation is significantly better than that of single pile foundation; the diameter and height of friction wheel in composite pile foundation have obvious influence on its horizontal bearing capacity, but its thickness has limited influence on the horizontal bearing capacity of composite pile foundation. It can be seen that the bearing capacity of composite pile foundation is significantly better than that of single pile.

1. Introduction
Composite pile foundation is a new type of wind power pile foundation, which is an optimization of single pile. Specifically, friction wheels are added to the single pile foundation to improve the bearing capacity of the foundation. Yang[1-3] et al. conducted centrifuge tests and numerical simulation on composite pile foundation, and concluded that the lateral bearing capacity of composite pile was significantly greater than that of single pile. Wang[4-7] and others have studied the lateral bearing capacity and vibration liquefaction of hollow friction wheel composite pile foundation and solid friction wheel composite pile foundation.

In this paper, ABAQUS software is used to establish a three-dimensional finite element model of composite pile foundation, and the advantages of horizontal bearing capacity of composite pile foundation compared with traditional single pile foundation and the action mechanism of friction wheel are compared and analyzed. At the same time, the parameters of friction wheel are changed, and the influence of friction wheel diameter, height and thickness on the bearing capacity of composite pile foundation is analyzed.

2. Model building

2.1 Composite pile foundation structure
Composite pile foundation consists of traditional single pile foundation and friction wheel installed on the periphery of pile body. As shown in fig. 1, the structural arrangement of the simulated composite pile foundation during service is shown in fig. 2. Single pile and friction wheel in composite pile foundation are made of Q345B steel.

2.2 Pile-Soil Finite Element Model

The soil environment and some parameters in the finite element simulation refer to a wind farm in an offshore area in eastern China. The values of model parameters input in ABAQUS finite element simulation software are shown in Tables 1 and 2.

| Parameter | $h_0$ (m) | $d_0$ (m) | $E$ (Mpa) | $v_0$ | $\gamma'$ (kN/m$^3$) | $C$ (kPa) | $\varphi$ (°) | $\psi$ (°) |
|------------|------------|------------|------------|--------|---------------------|----------|---------------|-------------|
| Silt       | 80         | 80         | 39.0       | 0.3    | 9.6                 | 4.7      | 32.5          | 15          |

| Parameter | $D$ (m) | $d$ (mm) | $H$ (m) | $l$ (m) | $E$ (GPa) | $v$ | $\gamma'$ (kN/m$^3$) |
|------------|---------|---------|--------|---------|-----------|-----|---------------------|
| Steel pipe pile | 4       | 60      | 60     | 75      | 210       | 0.3 | 7850                |
| Friction wheel | 10      | 60      | -      | 1       | 206       | 0.3 | 78.5               |

The established pile-soil finite element model is shown in fig. 3. Single pile and friction wheel adopt linear elastic constitutive model, and soil adopts Mohr-Coulomb elastic-plastic model. Since the center is a stress-sensitive position, the soil and friction wheel are gradually densely meshed along the radial direction from the edge, and C3D8R unit is adopted for pile and soil [8-11]. After repeated iterative calculation, the maximum vertical displacement caused by initial ground stress is within 10-5 orders of magnitude, and the accuracy meets the conditions for continuous calculation.
3. Analysis of calculation results.
This paper intends to reflect the stability and bearing capacity of pile foundation through lateral displacement and bending moment distribution of pile body. Therefore, the displacement and bending moment of the two pile types along the buried depth of the pile body are obtained under the horizontal loads of 1.5MN, 6MN and 12MN applied to the single pile model and the composite pile model respectively for comparative analysis. Among them, 0# pile is single pile foundation and 3# pile is composite pile foundation. Comparison of lateral displacement of pile body is shown in fig. 4, and comparison of bending moment of pile body is shown in fig. 5.

![Figure 4 Comparison of lateral displacement between of single pile and composite pile](image1)

![Figure 5 Bending moment comparison diagram single pile and composite pile foundation](image2)

As can be seen from fig. 4, the change trend of pile body displacement of composite pile foundation is generally similar to that of single pile foundation. Under the horizontal load of 1.5MN, the lateral displacement of pile body at the mud surface of composite pile foundation is reduced by 55.59% compared with that of traditional single pile foundation. The reduction rate is 30.84% under 6MN horizontal load and 26.31% under 12MN horizontal load. Compared with the traditional single pile foundation, the composite pile foundation has significantly reduced lateral displacement at the same height section, and the reduction ratio gradually decreases from the bottom of the pile to the top of the pile. The composite pile foundation can play a better horizontal bearing performance due to the existence of friction wheels.

As shown in fig. 5, the bending moment variation trend of composite pile foundation is similar to that of single pile foundation, and the maximum bending moment occurs at 55m depth. Comparing and analyzing the maximum bending moment of the two, under the horizontal load of 1.5MN, the reduction rate of the maximum bending moment of composite pile foundation pile body is 8.15% compared with the traditional single pile foundation; Under 6MN horizontal load, the reduction rate is 8.35%; Under 12MN horizontal load, the reduction rate is 10.68%. Similarly, the existence of friction wheel effectively limits the phase change of pile body and reduces the bending moment of pile body. Therefore, compared with single pile foundation, it has higher safety and stability performance.

4. Analysis of Influencing Factors of Friction Wheel

4.1 Influence of Friction Wheel Diameter
In ABAQUS software, five groups of models with friction wheel diameters of 8m(1.6D, 1# pile), 10m(2D, 2# pile), 12m(2.4D, 3# pile), 14m(2.8D, 4# pile) and 16m (3.2D, 5# pile) were established respectively, and 8-grade graded loads ranging from 0mn to 12mn were applied to them to calculate the influence of friction wheel parameters on the horizontal bearing capacity of composite pile foundation.
The lateral displacement and bending moment of pile body are also used to reflect the horizontal bearing capacity of pile foundation. The lateral displacement of composite pile foundation with different friction wheel diameters is shown in fig. 6, and the bending moment of pile body is shown in fig. 7. It can be seen from the figure that the existence of friction wheel effectively improves the horizontal bearing performance of composite pile foundation. And change the friction wheel diameter, under the same load, with the friction wheel diameter increasing, the lateral displacement of the pile gradually decreases, of which the 5# pile decreases the most, reaching 0.092m, which is 19.7% lower than the traditional single pile foundation; Moreover, the displacement of pile body also decreases with the increase of friction wheel diameter, which is also the largest reduction of pile No.5, reaching 23.8MN, which is 11.4% lower than that of traditional single pile foundation.

4.2 Influence of Friction Wheel Thickness
Five sets of finite element models with friction wheel thicknesses of 40mm(6#), 50mm(7#), 60mm(8#), 70mm(9#), and 80mm(10#) are established, and 8-grade graded loads in the range of 0 Mn to 12 Mn are also applied to them. The lateral displacement diagram and pile bending moment diagram at the mud surface of composite pile foundation with different friction wheel thicknesses are obtained as shown in fig. 8 and fig. 9 respectively. It can be seen that under the same load, the lateral displacement of composite pile decreases gradually with the increase of friction wheel thickness, of which the 10# pile decreases the most, reaching 0.034m, which is 28.9% less than that of traditional single pile foundation. Under the same level of load, the bending moment of pile body also decreases with the increase of friction wheel thickness, of which pile 10# decreases the most, 27.9MN, 13.4% less than that of traditional single pile foundation. From the bottom of the pile to 1.8D, the bending moment of the pile body began to change significantly.
4.3 Influence of Friction Wheel Height

Five sets of finite element models with friction heights of 0.5m, 1m, 1.5m, 2m and 2.5m respectively are established for calculation, and are divided into 8 levels of loads within the range of 0mn to 12mn to apply graded loads.

The lateral displacement diagram and pile bending moment of composite pile foundation with different friction wheel heights are obtained as shown in fig. 10 and fig. 11 respectively. From this, we know that under horizontal load, the lateral displacement and bending moment of composite pile foundation are smaller than those of traditional single pile foundation, and the reduction effect is obvious. Under the same level of load, the horizontal displacement of pile body gradually decreases with the increase of friction wheel height. When the height of friction wheel is 2.5m, the decrease is the most, 0.041m, which is 34.9% lower than that of traditional single pile foundation, and the effect is remarkable. The bending moment of pile body also decreases with the increase of friction wheel height. The composite pile foundation model of friction wheel with the same height of 2.5m has the largest decrease of 37.8MN, with the reduction ratio reaching 18.1%. When the bottom of the composite pile foundation goes up to 1.5D days, the bending moment of the pile body begins to change significantly.

5. Conclusion

In this paper, ABAQUS software is used to establish a three-dimensional finite element model of offshore wind turbine composite pile foundation. Compared with traditional single pile foundation, the bearing capacity advantage of the model is analyzed. The constraint effect of friction wheel on pile deformation is analyzed. The parameters of friction wheel are changed and the influence of different parameters on the bearing capacity of composite pile foundation is analyzed. The conclusions are as follows:

(1) Under the same load, the bearing capacity of composite pile foundation with friction wheel is obviously better than that of traditional single pile foundation. When the horizontal load is 12MN, the lateral displacement of the composite pile foundation is reduced by 26.31% and the maximum bending moment of the pile body is reduced by 10.68% compared with the traditional single pile, which has obvious effect.

(2) The change of friction wheel diameter has great influence on the bearing capacity of composite piles. The increase of friction wheel diameter gives full play to its restraining effect on pile deformation. Moreover, when the friction wheel diameter is less than 2.4 times of the pile body outer diameter, the decrease trend is very significant, and when the friction wheel diameter is greater than 2.4 times of the pile body outer diameter, the decrease trend is gradually stable.

(3) The change of friction wheel thickness has less influence on the bearing capacity of composite pile foundation. With the increase of friction wheel thickness, the lateral displacement and bending moment of composite pile foundation pile body gradually decrease, but the decreasing trend is
relatively slow. The increase of friction wheel thickness has limited improvement on the restraint effect of friction wheel.

(4) The change of friction wheel height has great influence on the horizontal bearing capacity of composite pile foundation. With the increase of friction wheel height, the displacement and bending moment of pile body of composite pile foundation gradually decrease. When the friction wheel height is 2.5m, the displacement and bending moment of pile body decrease by 34.9% and 18.1% respectively. The friction wheel gives full play to its restraining effect on the deformation of pile body and has remarkable effect.

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