Behavior of Pile Group Foundation for Offshore Wind Generator

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Introduction

As one of the most promising clean energy, offshore wind power attracted increasing attention recently. A lot of large-scale offshore wind generators were constructed in many countries. Large-diameter single pile was commonly used as the foundation for the wind generator. Its deformation and bearing capacity were investigated using different approaches. Field tests were conducted to observe the relationship between soil resistance and pile deflection subjected to lateral load, offering important instructions on wind generator pile design [1-2]. Centrifuge model tests were used to study the response of piles and soil-pile interaction under horizontal loading conditions [3-4]. The finite element method was used to reveal the characteristics of large diameter single pile in dense sand [5]. Recently, for example, in China, pile group was used as the foundation for offshore wind generator rather than the single pile [6] because the pile group could reduce the diameter of the pile so as to lower the requirement for pile driving barge. This paper is to investigate the performance of pile group in clayed soil using the three-dimensional finite element analysis.

Numerical simulation method

A large-scale finite element software ABAQUS was used for the three-dimensional numerical analysis of pile foundation of the offshore wind generator. The ideal elastic-plastic model with the Mohr-Coulomb yielding criterion was employed for the soil. The pore pressure was considered as a degree of freedom at each node. The materials of the pile and superstructure were modelled using the linear elastic model. The bottom boundary are restrained in all direction, meanwhile, the four side boundaries are only limited in the horizontal direction.

The numerical method was employed to simulate a centrifuge model test on the single pile under dynamic horizontal loading conditions [3]. The acceleration of gravity was simulated at 490 m/s^2 (50 g) as the model in the test was applied with the centrifugal acceleration of 50 g. A pile was inserted into the soil to a depth of 280 mm that was equivalent to 14 m in the prototype. Its diameter of the pile was 50 mm that was equivalent to 2.5 m in the prototype. A dynamic horizontal load history of 390 s, which could be divided into two horizontal load components (P_1 and P_2), was applied at the top of a steel pipe pile. P_1 was a monotonic load component, which stayed at 50 N at the model scale (125 kN at the prototype scale) during the first period of early 330 s and then increased to 300 N at the model scale (750 kN at the prototype scale) in the remainder 60 s. P_2 is a sinusoidal cyclic load component, which had an amplitude of 40 N at the model scale (100 kN at the prototype scale) and a frequency of 1 Hz at the model scale (0.02Hz at the prototype scale).

Table 1 lists the material parameters of soil, pile and superstructure. The numerical analysis results were compared with the centrifuge model test results [3], as shown in Figs. 1-2. It can be seen that the prediction results on the horizontal displacement and bending moments of the pile was close to the test observations. This demonstrated that the used numerical method was effective to analyze the behavior of pile-soil interaction system under the condition that the offshore wind generator experienced.

Application

The behavior of a five-pile foundation of the wind generator project was analyzed using the proposed method. Two types of superstructures, a steel jacket and a truss, were considered to discuss the effect of superstructure on the response of the piles (Fig. 3). Table 1 shows the material parameters of the soil, pile and superstructure. A combination load history was applied at the top of the superstructure, including a monotonic lateral load component *P*1’ (34 MN) and a sinusoidal cyclic lateral load component *P*2’ (amplitude: 1.6 MN), a vertical load *V*’ (3.4 MN) and a horizontal bending moment *M*’ (155 MNm).

The analysis results showed that the horizontal displacement at the top of the superstructure increased during loading (Fig. 4). The increase rate can be observed to increase as the horizontal load increased: this may be because the soil near the piles gradually yielded with the application of loading. The horizontal displacement of the foundation using the jacket superstructure was significantly greater than the one using the truss superstructure. Such a difference increased as the load increased.

The distributions of the bending moment and axial force of two typical piles were examined (Figs. 5-6). It can be seen that the bending moment and the axial force of the pile reached their maximums close to the soil surface. The absolutes of the bending moment of the piles using the jacket superstructure were significantly greater than the ones using the truss superstructure, while the axial force were smaller. The differences were more evident near the soil surface. This demonstrated that the superstructure had a considerable effect on the response of the piles.

The analysis results also demonstrated that the pile group exhibited different bearing mechanism from the single pile under the condition that the offshore wind generator experienced. For the single pile foundation, the bending moment that was applied on the foundation was borne by the pile itself (Fig. 2). However, for the pile group, the piles offered a resistance moment as a whole by tensioning or compressing in the axial direction at different piles. Therefore, additional axial force was introduced to the piles so that several piles may experience tension (e.g., Fig. 5).

Conclusion

A three-dimensional numerical analysis model was set up to simulate pile foundation of offshore wind generator and confirmed to be effective by simulating the centrifuge model tests.

The behavior of a five-pile foundation of the wind generator project was analyzed. The results showed that the superstructure had a considerable effect on the response of the piles. Increasing the rigidity of the upper structure could reduce the displacement and the bending moment of piles. The piles in the pile group foundation offered a resistance moment as a whole by tensioning or compressing in the axial direction at different piles. Such a bearing mechanism was different from the single pile.

References

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Table 1-- Parameters for single-pile foundation simulation

material	density	Young's modulus	Posson's ratio	friction angle	cohesion	permeability
soil in centrifuge test	1385 kg/m³	0.4 MPa	0.45	15	3000 Pa	10^{-6} m/s
soil in practical project	1500 kg/m³	4 MPa	0.4	30	5000 Pa	10^{-6} m/s
concrete	2500 kg/m³	20 GPa	0.3	-	-	-
steel	7850 kg/m³	200 GPa	0.3	-	-	-

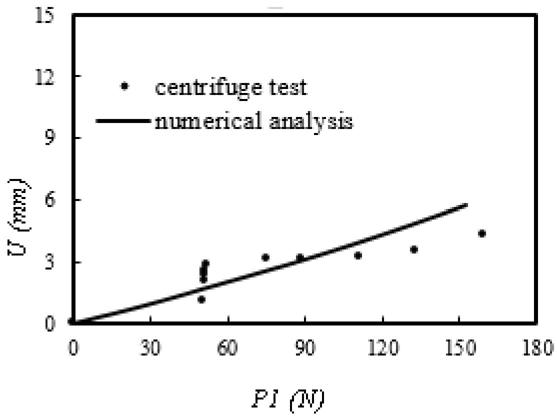

Fig. 1— Relationship between horizontal load and displacement of pile in centrifuge test. P1, monotonic load component; U, displacement at top of pile.

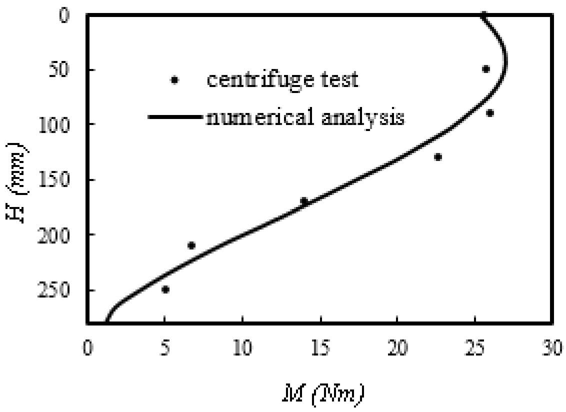

Fig. 2—Bending moment of pile at 200s in centrifuge test. M, bending moment; H, distance from soil surface.

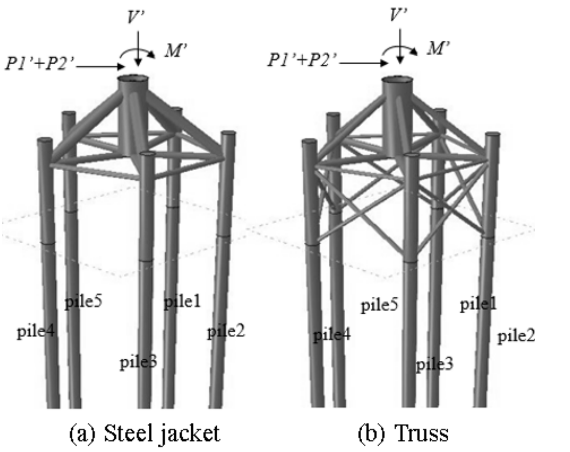

Fig. 3—Two schemes with different superstructures. The left one is steel jacket. The right is truss.

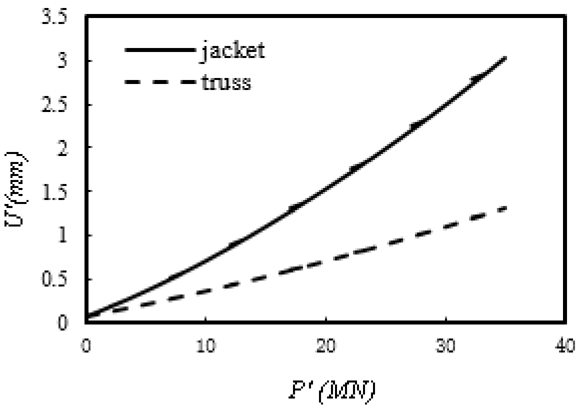

Fig. 4—Relationship between horizontal load and displacement in practical project analysis.
P1', monotonic load; U', horizontal displacement at the top of the superstructure.

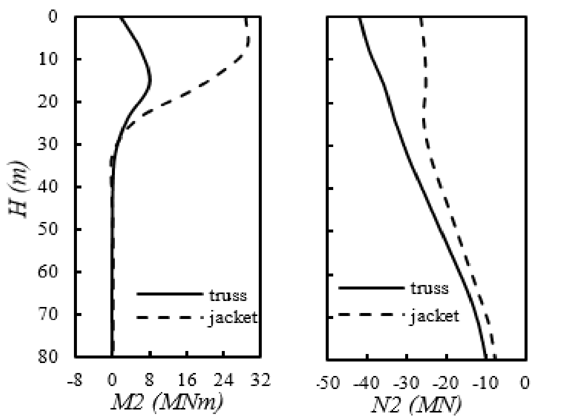

Fig. 5—Response of pile2 in practical project analysis. M2, bending moment of pile2; N2, axial force of pile2; H, distance from soil surface.

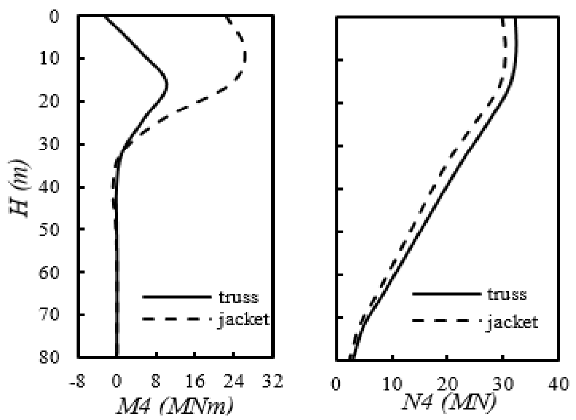

Fig. 6—Response of pile4 in practical project analysis. M4, bending moment of pile4; N4, axial force of pile4; H, distance from soil surface.