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Bearing Behavior of a Hybrid Monopile Foundation for Offshore Wind Turbines

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Abstract**—**Offshore wind energy provides a huge potential for the expansion of renewable energies to the coastal countries. High demands are required concerning the shape and type of foundations for offshore wind turbines (OWTs) to find an economically, technically and environmentally-friendly optimal solution. A promising foundation concept is the hybrid foundation system, which consists of a steel plate attached to the outer side of a hollow steel pipe pile. In this study, the bearing behavior of a large diameter foundation is analyzed using a 3-dimensional finite element (FE) model. Non-linear plastic soil behavior is considered. The results of the numerical simulations are compared to highlight the priority of the hybrid foundation to the conventional monopile foundation.

Keywords**—**Hybrid foundation system, mechanical parameters, plastic soil behaviors, numerical simulations.

I. INTRODUCTION

THERE are several types of foundation systems available to the design of OWTs. The preferred foundation system will be dependent on the local seabed soil conditions and the size of OWTs. Several typical types of foundations have been widely used in engineering practices, such as gravity foundation, suction caisson (including tripods), large-diameter monopile, etc. There are also instances where a combination or hybrid arrangement of foundation elements may prove the most economical and provide significant ultimate capacity. This paper presented a 3-D hybrid foundation system model with the FEM software ABAQUS (see Fig. 1). In most cases, these kinds of piles are vertical and are designed to bear static vertical loads, cyclic horizontal loads and bending moment. Design methods have been developed accordingly and have been proven efficient and safe. Design methods for both static and cyclic loading have been investigated extensively as part of the development of the offshore resource development industries. More recently, the monopile has been installed in relatively shallow water depths with diameters beyond 5.0 m [3].

The feasibility in using monopile foundations in deep water is determined by both the cost of installation and the compliant nature of the structure. With regard to the second aspect, many efforts have been contributed by the theoretical studies of a guyed monopile system [1]; however, this method is required to be fully explored. An alternative approach is to incorporate a bearing plate at the mudline, which could add a degree of restraints to resist lateral loads. This hybrid monopile-footing concept is like that of a retaining wall with a stabilizing base [9]. A series of 1-g tests [12] and centrifuge model tests [7], [8] of the hybrid system in which the bearing capacity was rigidly fixed to the pile reported that, (1) the vertical bearing capacity of the hybrid system is generally greater than the sum of the individual components (pile and footing), (2) the lateral stiffness and load capacity of the hybrid foundation are significantly improved in contrast to that of the pile alone, and (3) the initial contact stress between the footing and the soil has a significant influence on the lateral stiffness of the system response. Similar findings were also reported for physical and numerical model studies on sand [4], [5] and some full-scale testing and numerical analyses [7]. The previous studies mainly focused on the bearing characteristic of large-diameter monopile foundation rather than hybrid large-diameter foundation with an attached plate, which is at present the most potential foundation type for OWT in offshore area. In this study, a 3-dimentional FE model for foundation-soil interactions was established to analyze the bearing mechanism and the ultimate bearing capacity of the hybrid foundation system.

II. NUMERICAL MODEL

FE Mesh and Constitutive Models of Materials

The ultimate bearing capacity and displacement of a hybrid steel pile foundation under a combination of uniform load, concentrated force and bending moment can be simplified as a plane-symmetric problem. A three-dimensional plane-symmetric FE model is proposed for simulating the pile-soil interaction using the FE software ABAQUS.

Fig. 1 shows the geometry of the FE model. It mainly includes the foundation and surrounding soil. The foundation is welded together by the inner and outer surfaces of two thin-walled steel pipes. A thin-walled plate is welded to the upper edge of the exterior surface of the steel pipe, and there exists soil-plugs inside the pile interior surface. The soil and foundation are composed of three-dimensional eight-node solid elements (C3D8). In order to improve the calculation efficiency, the elements are divided into denser and closer grids. In total, approximately 46,000 units are used. The surface contact method is a critical issue for efficient simulation of complex pile-soil interactions. Therefore, a contact pair algorithm was proposed to describe the constitutive relationship between the exterior of the foundation and the surrounding soil, and the interior and the surrounding soil contacting the surface.

The Mohr-Coulomb model is used to simulate the elastoplastic behavior of soil due to the following reasons: (1) the failure of the pile is not during the loading process; (2) the elastic modulus of each component of the pile foundation is

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assumed to be linear elastic under different mechanical parameters.

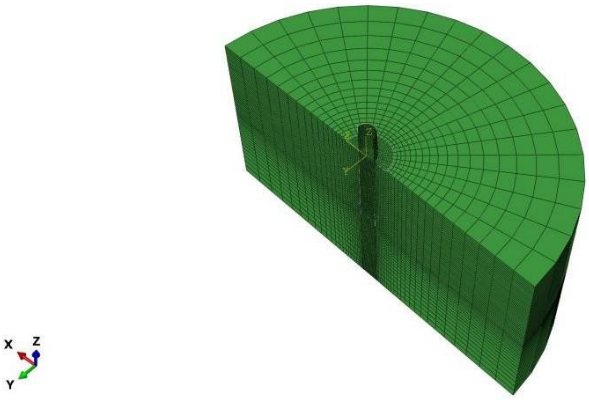

Fig. 1 FE mesh

Boundary Conditions and Loading Conditions

As explained in Fig. 1, the top of the soil is regarded as a free constraint, the front of the model is a plane symmetric constraint, all the degrees of freedom in rotation in the x and z directions and the freedom in translation in the x and y directions Degrees are constrained. At the bottom of the model, the parallel degrees of freedom in the three directions of x, y, and z are fixed. The whole load effect can be obtained by combining the individual characteristic load effects due to the respective individual environmental load types. Each load case is defined and simplified as the combination of two or more environmental load categories.

Model Parameters

As a case study, the parameters for the examined foundation are listed in Table I, considering the practical condition of the water depth and the design parameters of similar preceding projects. We modified the soil and pile parameters respectively to analyze the bearing behavior of the foundation under a variety of ULS conditions and soil categories. The ultimate capacity and displacement of traditional large monopile foundation and the hybrid system were compared as a quantitative analysis. In addition, the elastic modulus was modified accordingly to obtain its effect to the bearing behavior of the whole foundation; the vertical load variables were modified to obtain its effect to the bending moment.

The parameters for the examined foundation were listed in Tables II and III.

III. MODEL RESULTS

A monopile with a diameter of $D = 6$ m and an embedded length below sea bed of $L = 30$ m was taken as the basic case. With an assumed water depth of 30 m the resultant design wave load acts at $h = 10$ m above sea bed level, i.e., $h/l = 1/3$.

For a resultant horizontal load of 1 MN, which is a possible design load for the considered water depth, the horizontal (bedding) stresses acting on the pile in the symmetry plane are shown in Fig. 2. For the horizontal force of $H = 1$ MN and the bending moment at sea bed level of $M = 40$ MN.m, the pile displacement at sea-bed level amounts to about $w = 3$ m.

TABLE I
PARAMETERS FOR PILE AND FOOTING OF THE HYBRID FOUNDATION SYSTEM

	Wall thickness (m)	Embedded Pile length (m)	Length/Height L/D (m)	Pile/Plate Outer diameter D (m)	Mass Density ρ kg/m^3	Young's modulus E (GPa)
pile	0.08	30	40	6	7.85	/
plate	7.42	/	0.08	15	7.85	/

TABLE II
FRICTION ANGLE AND DILATION ANGLE OF SOIL

Soil	Friction angle (°)	Dilation angle (°)
Sand	45	7.5
	35	
	25	
	45	5
	35	
	25	

TABLE III
YOUNG'S MODULUS AND VERTICAL LOAD OF MONOPILE

Vertical load	Es (plate)	Es of pile (plate with friction)	Es of pile (plate non-friction)
1 GN	750 GPa	210 GPa	210 GPa
2 GN	700 GPa	180 GPa	180 GPa
3 GN	650 GPa	150 GPa	150 GPa
4 GN	600 GPa	120 GPa	120 GPa
5 GN	550 GPa	90 GPa	90 GPa
6 GN	500 GPa		
	450 GPa		

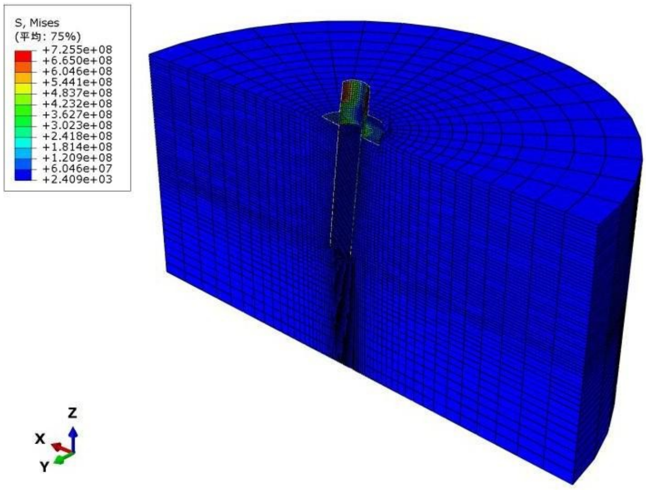

Fig. 2 Mobilized bedding pressure for a monopile with $D = 6$ m, $L = 40$ m in soil, $H = 1$ MN, $M = H{\cdot}h = 40$ MN.m

From a practical point of view, the design procedure for a monopile foundation depends mainly on the calculation of the horizontal displacement with respect to the applied loading conditions.

Variation of the Parameters of the Basic Model

In the scope of a parametric study the vertical load, the bending moment and the elastic modules of both pile and plate were varied in order to take different water depths or load combinations into consideration. Additionally, the embedded soil with a variety of internal friction angles and dilation angles were analyzed. The results are shown in Figs. 3-8.

Comparison between Monopile and Hybrid Foundation

Both of the two pile categories have differences and similarities. They are both made from steel and were manufactured into hollow pile, embedded in the mud, bearing vertical load, horizontal load and bending moment in real engineering practices. However, from Figs. 3 and 4, their ultimate capacity and displacement have a significant difference. Because of the attached plate, the results demonstrate that hybrid foundation system shows a smaller deflection compared with monopile under equivalent load combinations in real practices.

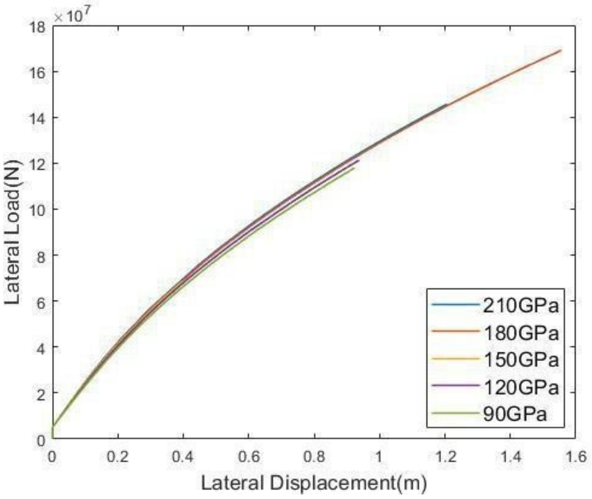

Fig. 3 Force-displacement curves for a hybrid foundation *D* = 6 m, *L* = 40 with pile Young's modulus of 90 GPa, 120 GPa, 150 GPa, 180 GPa, 210 GPa, respectively

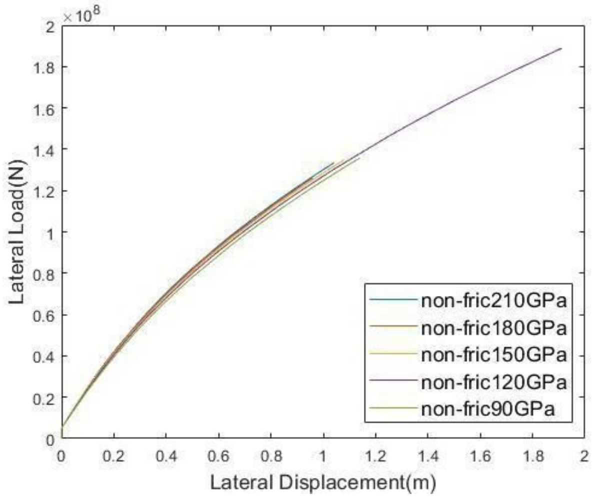

Fig. 4 Force-displacement curves for a monopile *D* = 6 m, *L* = 40 with pile Young's modulus of 90 GPa, 120 GPa, 150 GPa, 180 GPa, 210 GPa, respectively

The Variation of Plate with and without Friction

From Fig. 5, it is evident that the additional of the footing provides lateral restraint to the monopile with various Young's modulus ranging from 90 GPa to 210 GPa bearing equivalent load combinations.

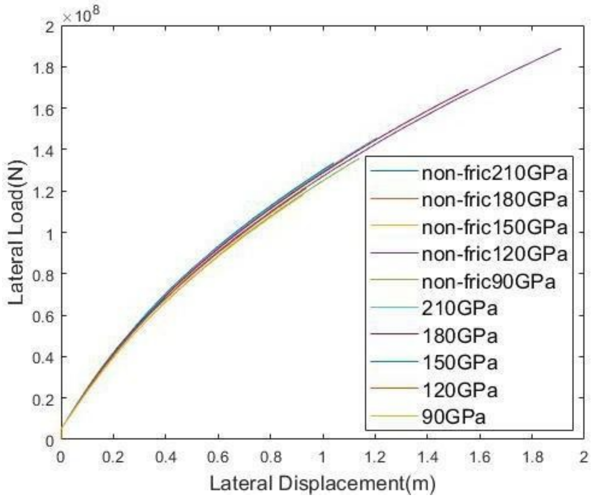

Fig. 5 Comparison of force-displacement curves of hybrid foundation and monopile with pile Young's modulus of 90 GPa, 120 GPa, 150 GPa, 180 GPa, 210 GPa, respectively

The Variation of the Elastic Modulus of Pile

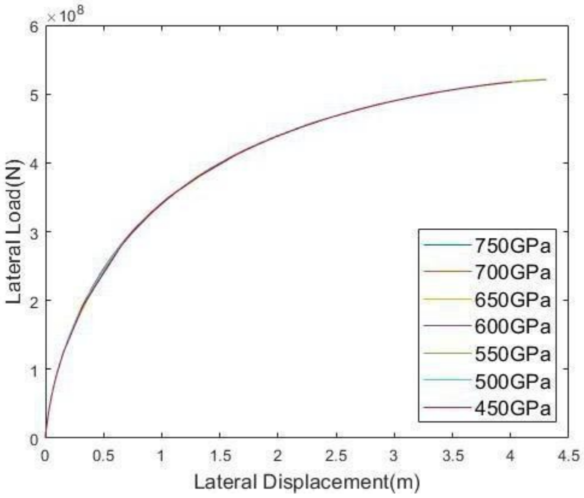

Fig. 6 Force-displacement curves for a hybrid foundation *D* = 6 m, *L* = 40 with pile Young's modulus of 450 GPa, 500 GPa, 550 GPa, 600 GPa, 650 GPa, 700GPa, 750GPa, respectively

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The Variation of Vertical Load under Other Load Combinations

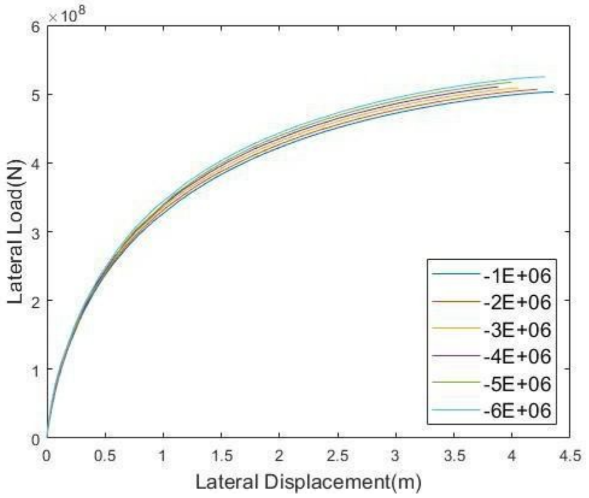

Fig. 7 Force-displacement curves for a hybrid foundation $D = 6$ m, $L = 40$ with vertical load of, respectively: -1×10^6 N, -2×10^6 N, -3×10^6 N, -4×10^6 N, -5×10^6 N, -6×10^6 N

The Variation of Internal Friction Angle (FA) and Dilation Angle (DA)

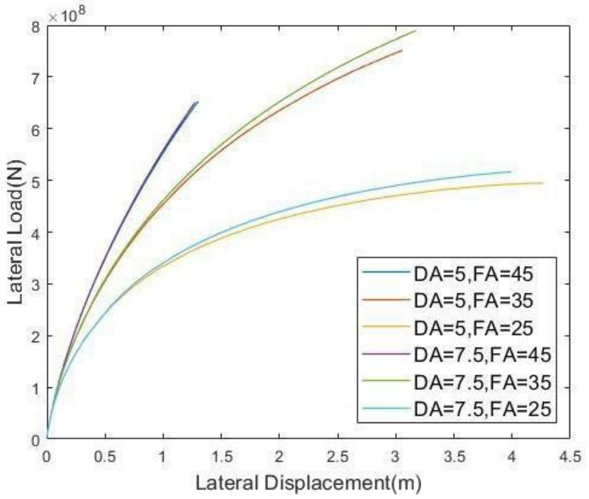

Fig. 8 Force-displacement curves for a hybrid foundation $D = 6$ m, $L = 40$ with various dilation angles (DA) and internal friction angles (DA)

IV. DISCUSSIONS

The numerical study demonstrates that the use of a bearing plate can enhance the lateral capacity of a monopile under different load combinations. The hybrid foundation arrangement was investigated, in which the bearing plate was either fully fixed to the pile (coupled) or free to slide vertically on the pile shaft (decoupled).

In the coupled arrangement, the lateral capacity of the system was derived from (1) the lateral resistance of the pile, (2) the lateral resistance of plate, and (3) the resisting moment developed at mudline as the plate rotates. The interaction that develops in the coupled system is that both the interface interaction friction and increased vertical load can only develop a certain value associated with the ultimate bearing stress of the underlying soil.

In the decoupled arrangement, the interaction is much simpler, the reasons are as follows: (1) the connection between the pile and bearing plate is assumed to be unable to apply a resisting moment at the mudline; (2) the plate is free to move vertically on the pile with negligible frictional resistance. And because it can be assumed that the load applied to the plate remains relatively constant and tiny throughout the loading process, the interface friction would also remain constant throughout the simulation process. The analysis of the decoupled arrangement is therefore relatively straightforward when the lateral capacity is derived from the lateral capacity of the pile, including any effects of the platesurcharge.

In the numerical studies, the development of the lateral capacity of the hybrid systems is influenced by the scale effect associated with the categories of soil used in the calculations. Such scale effects are well reported elsewhere [10] and are associated with the absolute relative displacement required for the soil to achieve its peak and critical state values of mobilized friction. Some relative lateral displacement is required to fully mobilize the interface friction, the mudline moment and the pile lateral capacity. All of these components may have different mobilization displacement that are likely to be an inherent scale effect of the model, which is difficult to quantify, but is likely to overestimate the lateral movement required to develop ultimate lateral capacities for the hybrid systems with respect to a corresponding prototype.

V. CONCLUSIONS

A 3-D plane-symmetric FE model is proposed to simulate the interaction between the hybrid foundation system and the neighboring soil. As a case study, the total load values applied on the foundation under different ULS conditions is examined with the proposed numerical model; the function of plate and the effect of the vertical load is considered and calculated with ABAQUS. The deformation in various ULS conditions is examined with the proposed numerical model. The present design of foundation can satisfy the tilt criterion of OWT. Plate could amplify the displacement of the foundation and decrease its ultimate bearing capacity.

According to the results of the numerical calculations carried out for large-diameter monopiles for high design loads, the following conclusions can be made:

1. A hybrid foundation system can be formed from the combination of a pile and a bearing plate. Different systems have fundamental differences in their response and development of lateral capacity.
2. The lateral response of the hybrid system is a function of the plate and pile geometry and stress developed between the bearing plate and underlying soil.
3. For the decoupled system, the initial bearing stress is provided by dead load supported by the plate and is readily determined.
4. For the coupled system, the lateral capacity is derived through pile resistance, the interface friction between the

plate and underlying soil, and the restoring moment generated at the mudline by the rotating bearing plate.

5. For the decoupled system, the lateral capacity is derived through the pile lateral resistance and the bearing plate interface friction.

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