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Numerical Study on the Effect of Spudcan Penetration on the Jacket Platform

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Abstract—How the extraction and penetration of spudcan affect the performance of the adjacent pile foundation supporting the jacket platform was studied in the program $FLAC3D$ depending on a wind farm project in Bohai sea. The simulations were conducted at the end of the spudcan penetration, which induced a pockmark in the seabed. The effects of the distance between the pile foundation and the pockmark were studied. The displacement at the mudline arose when the pockmark was closer. The bearing capacity of this jacket platform with deep pile foundations has been less influenced by the process of spudcan penetration, which can induce severe stresses on the pile foundation. The induced rotation was also satisfied with the serviceability constraints.

Keywords—Offshore foundation, pile-soil interaction, spudcan penetration, $FLAC3D$.

I. Introduction

WIND power as a kind of clean and renewable energy has great potential for development, particularly for the coastal islands, grassland, and rural area. The application of wind energy can reduce the emission of carbon dioxide and change the polluted environment, which is for sure a global aim. The development of wind power is not only compatible with the atmospheric environment, but also inseparable from the national economy. At present, wind power generation is the most mature technology in the new energy and the most prospect of commercial development of power generation. The wind turbine generator installed offshore is generally fixed on a designed foundation. The special foundation is required to have excellent serviceability under ultimate conditions. The wind turbine generator is supported by the jacket platform with pile foundations, which is installed using the jack-up rigs. During the extraction and penetration of the spudcans closed to the jacket piles, a large volume of soil displaced may induce severe stresses on the piles supporting the jacket platform [10], [13], [14]. The potential effects of the spudcan extraction and penetration on the jacket piles have been studied by many other researchers. Mirza proposed a simple procedure to evaluate the foundation interaction effects, from the stage spudcan penetration, over the stage disturbed soil movement profiles to the stage pile loads [10]. For the jacket platform, an increase of soil loads transmitted to the pile foundation during the spudcan penetration and a reduction of the lateral capacity of the pile foundation was observed. Chow investigated the effects of spudcan movements on the lateral and axial behavior of adjacent fixed-head piles using a series of centrifuge model tests [5]. The test results illustrated that the most critical period for platform piles is at the end of spudcan installation, and the lateral pile behavior is more severely affected than the axial pile behavior. Wang et al. illustrated the influences of spudcan penetration on pile groups of jacket platform [15]. The main findings were that the lateral displacement and moment and shear force of pile group increased with the increase of the spudcan penetration depth. Fan et al. studied the effect of spudcan penetration on an adjacent pile group, and found that the Y-modifier tended to decrease during spudcan penetration, however, the reduction was limited [16].

Numerical simulation has been commonly employed to investigate the effects of soil movements due to spudcan penetration or extraction on the close adjacent pile foundation performance. Lyons et al. simulated the kind of effect at the final state of spudcan penetration using 3D finite element analysis [9]. They pointed out the inadequacy of plane strain and emphasized the requirement to perform the 3D finite element analysis.Tan et al. conducted the 3D numerical simulation of the continuous spudcan penetration using the large deformation finite element method to investigate the effect of the spudcan penetration on the adjacent pile [12]. Some simulations depending on the Eulerian finite element technique were carried out to simulate continuous spudcan penetration in both homogenous and layered soil profiles [7], [6], [11]. In this paper, the numerical simulation using program $FLAC3D$ was conducted to investigate the effect of spudcan penetration on the performance of adjacent pile foundations. A sensibility on the distance between the spudcan penetration and the pile foundation was studied.

II. Project Overview

This project is located in the Bohai Sea near Dalian, Liaoning province, China, as described in Fig. 1. 78 wind turbine generators with a total power of 6.45 MW are being installed. The reanalysis data from European Centre for Medium-Range Weather Forecasts (ECMWF) indicate the huge regional wind energy resources. According to the meteorological history in the last 60 years, the annually-averaged temperature is 22.5 $°C$, the annually-averaged rainfall is 2310.7 mm and the annually-averaged wind speed is 3.0 m/s. The historical maximum wind speed is 52.5 m/s recorded in 3 s and 34.6 m/s recorded in 10 min. The kinetic and potential energy of waves is also huge throughout the year. In such a complex environment, the quadrupedal jacket platform with pile foundation was employed to support the wind turbine and

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ensure its good serviceability at the ultimate state. This kind of supporting system must be installed utilizing the jack-up rigs.

The geotechnical conditions were identified by adopting the standard penetration tests and laboratory tests. In the scope of the drilling depth, combined with the regional geological data, it was indicated that the site strata were mainly the sedimentary layers, i.e. the Quaternary Holocene Marine Sedimentary Strata (Q_4^m), the Quaternary Holocene Sea-Land Interaction Sediment Strata (Q_4^{mc}) and the Quaternary Late Pleistocene Intercontinental Sedimentary Strata (Q_3^{mc}). The detailed soil properties are listed in Table I. γ' is the submerged weight; c_u is the undrained shear strength; ϕ is the firction angle; E is the Young's modulus and f_s is the friction pressure in unit shaft area.

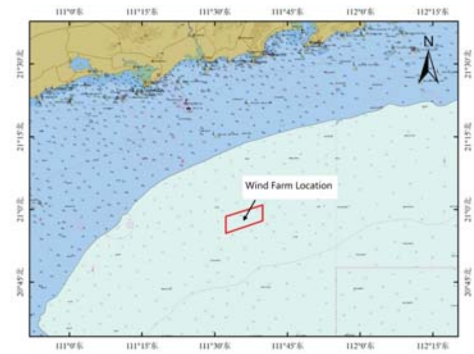

Fig. 1 The location of wind farm

TABLE I
MATERIAL PARAMETERS OF MULTI SOIL LAYERS

$Soil\ layer$	$depth$ $[m]$	γ' $[kN/m3]$	C_u $[kPa]$	ϕ $[°]$	E $[MPa]$	f_s $[kPa]$
1-1 silt	-51.00	7.0	16	/	1.6	5
1-2 silt	-57.50	7.5	20	/	3	11
2-1-1silty clay	-64.00	8.5	30	/	7.5	29
2-1silty clay	-71.60	9.0	45	/	11	42
2-2 silty clay	-79.20	8.5	80	/	25	55
3-4-1fine silty sand	-87.30	9.0	/	33	50	75
3-1clay	-88.80	8.4	130	/	39	65
3-4-1silty sand with clay	-96.10	9.0	/	33	35	59
3-2 clay	-100.20	8.6	170	/	51	72
3-2 clay	-105.20	8.3	190	/	57	45
3-5 coarse sand	-115.20	10.3	/	37.5	80	118
3-2 silty clay with sand	-121.40	8.2	220	/	66	69
4-1clay	-131.50	8.0	230	/	69	70

III. NUMERICAL ANALYSIS

As introduced, the extraction and penetration of the spudcans will induce a stress arrangement around the adjacent piles supporting the jacket platform. The guidance notes on geotechnical performance of spudcan foundations of US-ABS provide the generalized soil condition of footprint indicating the distributions of the heavily remoulded zone, the moderately disturbed zone, and the less disturbed zone, as the illustration in Fig. 3. It was also recognized that a pockmark after the penetration of the spudcan was remaining. Depending on the findings of Chow [5], the most critical period for a platform, the investigations at the end of spudcan penetration can be conducted. It can be simplified conservatively to

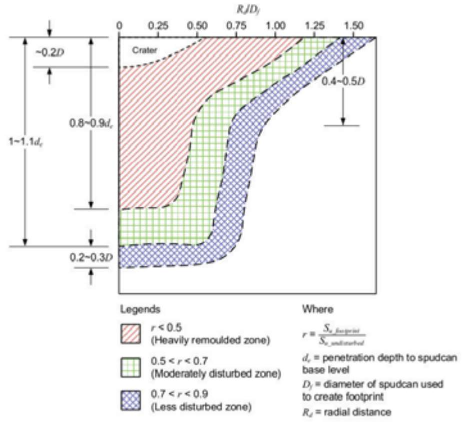

Fig. 2 Generalized soil condition of footprint according to the guidance notes of US-ABS [2]

simulate a pockmark for figuring out the corresponding effects on the performance of the pile foundations. Not only the investigations of the whole supporting system but also the investigations of the monopile are considered. Wang et al. indicated that lateral displacement, moment, and shear force of pile increased with the increase of the spudcan penetration depth [15]. Therefore, the influence of the depth of the spudcan penetration was not considered in this paper. Instead, the influence of the distance between the pockmark and monopile was investigated.

A. Numerical Model

Fig. 3 describes the numerical model of the jacket platform with pile foundations in the program $FLAC3D$. The jacket platform supported by four pile foundations was built closed to the pockmark induced by the spudcan penetration. The seabed was modeled by a soil cuboid with a length of 150 m, a width of 120 m, and a height of 106 m. The pockmark diameter of 16 m and pockmark depth of 18 m were considered equivalent to the impact area of spudcan. The embedded pile foundations with a diameter of 2.8 m and a length of 92 m were modeled by the Liner elements.The Liner elements can automatically create an interface attached to them for simulating the pile-soil interaction and sliding between the pile and soil [1]. The jacket platform was modeled by the Beam elements and the Liner elements, which was considered stiff enough not to create additional deformations. Since the researches focused on the performance of the pile foundation, the x-, y- and z-velocity at the bottom, and x- and y-velocity on sides equal to zero were employed as the boundary conditions.

For reflecting the soil responses under loadings, the constitutive model Mohr-Coulomb was employed. The corresponding material parameters of each soil layer are listed in Table I. It was assigned for the jacket platform with pile foundations with an elastic modulus of $2.1{\cdot}10^8$ kPa and a Poisson's ratio of 0.3. 80 % of surrounding soil properties were assumed as the interface parameters to refect the pile-soil interaction.

Table II represents the horizontal loadings applied on the top of the jacket platform. These loadings include the extreme loads without the safety factor and the wind loads. For the foundation design under marine conditions, the wave loads must be considered. It is commonly acknowledged that the wave force acting on the pile can be determined using Morison's equation. For D/L $\leq$ 0.2 of pile, the equation can be expressed as [4]:

$$f_{wy} = \frac{1}{2}\rho_w C_D D \left\{u - \frac{\partial y}{\partial t}\right\} \left|u - \frac{\partial y}{\partial t}\right| + C_M \rho_w \frac{\pi D^2}{4} \left\{\frac{\partial u}{\partial t} - \frac{\partial^2 y}{\partial t^2}\right\} \tag{1}$$

where f_{wy} is united wave force acting on the pipeline; ρ_w is the water density; C_D and C_M are the drag and inertia coefficients, respectively; D and L are the pile diameter and length, and u is the horizontal velocity of water around the pile. However, for such a complex system, the wave forces acting on the structure were computed using commercial program ANSYS.

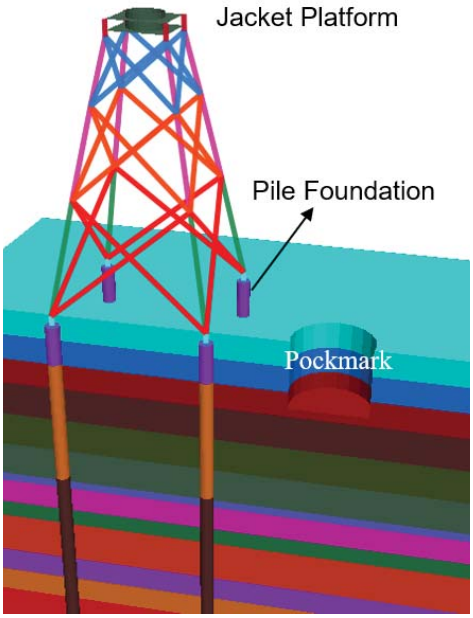

Fig. 3 The description of the numerical model

TABLE II
LOADS ACTING AT THE TOP OF THE JACKET PLATFORM

	F_x $[kN]$	F_z $[kN]$	M_x $[kNm]$	M_z $[kNm]$
Loadings	1122.03	-8751.12	71750.7	-827.085

B. Parametric Study

The increased penetration depth of spudcan arose the lateral displacement, the moment, and the shear force of the adjacent pile [15]. The guidance notes of US-ABS indicated that the soil around the pockmark induced by the spudcan penetration was remoulded, which caused severe stress on the adjacent piles. Thus, a qualitative analysis of the distance between the pockmark and the adjacent pile must be conducted. According to Fig. 3, R_d/D_f was selected equal to 0.625, 0.75, 1.0 and 1.125. The impact radial distance R_d equaled to 10 m, 12 m, 16 m, and 18 m when the diameter of spudcan D_f was 16 m. Note that the jack-up rigs were penetrated in this project at there 12.2 m away from the pile foundation of the jacket platform.

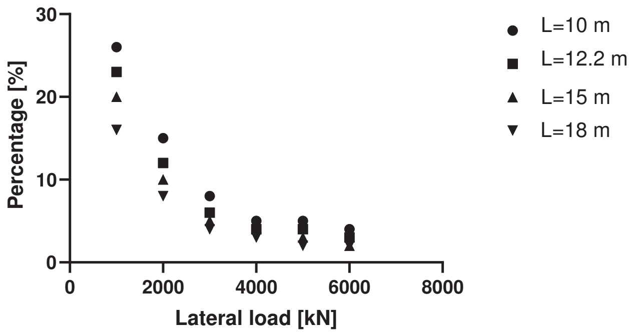

Fig. 4 Increase of displacements at mudline induced by the pockmark with various distances away from the pile foundation

Table III and Fig. 4 represent the increase of the displacements at the mudline caused by the pockmark with various distances away from the adjacent pile foundation, which also indicates the effect of the distance on the bearing capacity of the pile foundation. The displacement at the mudline increased with an increase in loading up to 6000 kN. The effects of the distance on the displacement at the mudline were reduced when the distance of the pockmark away from the pile foundation increased. However, the displacements caused by large loadings were similar when the distance varied.

Figs. 5, 6 and 7 represent the distributions of the lateral displacements, the shear force, and the moment of the monopile. The lateral displacement, shear force, and moment in the following context mean the additional values caused by the pockmark. The lateral displacement in the shallow soil layer is much greater than this in the deep soil layer. The maximum lateral displacements were at the mudline when the pockmark is located at there 10 m or 12.2 m away from the monopile. For the pockmark 16 m or 18 m away from the monopile, the maximum lateral displacements occurred in the shallow soil layer near the mudline. The distributions of shear force were similar when the distance varied. The maximum shear force occurred at the shallow depth. The closest pockmark caused the largest shear force. The distributions were almost identical when the distances were 16 m and 18 m. The maximum moments, approximately -1400 kNm, occurred at the shallow depth. The maximum moments were smaller when the distances were 10 m and 12.2 m, which indicated a limited influence on the moment.

C. Numerical Simulation Results

It is well acknowledged to limit the angular rotation lower than the designed angular rotation for ensuring the wind

TABLE III
COMPARISON OF DISTURBED DISPLACEMENTS TO THE DISPLACEMENTS WITHOUT DISTURBANCE

	no disturbance	distance 10 m		distance 12.2 m		distance 15 m		distance 18 m	
Loadings [kN]	Disp. Mudline [mm]	Disp. Mudline [mm]	Increase %	Disp. Mudline [mm]	Increase %	Disp. Mudline [mm]	Increase %	Disp. Mudline [mm]	Increase %
1000	38.2	48.3	26.44	46.9	22.77	46.0	20.42	44.2	15.71
2000	82.5	94.5	14.55	92.0	11.52	91.0	10.3	89.2	8.12
3000	139.1	150.0	7.84	147.5	6.04	146.0	4.96	145.0	4.24
4000	210.0	221.0	5.24	219.0	4.29	218.0	3.81	217.0	3.33
5000	295.0	310.0	5.08	307.0	4.07	304.0	3.05	302.0	2.37
6000	399.0	416.0	4.26	410.0	2.76	408.0	2.26	406.0	1.75

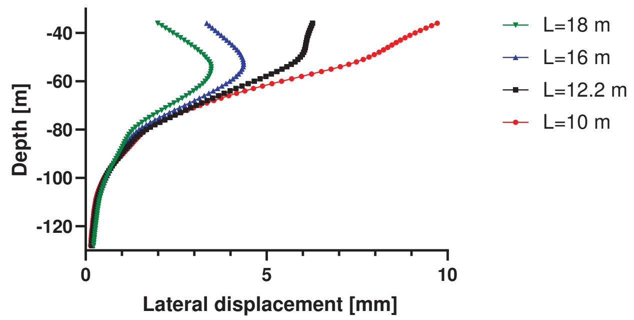

Fig. 5 The additional distribution of the lateral displacements of the monopiles

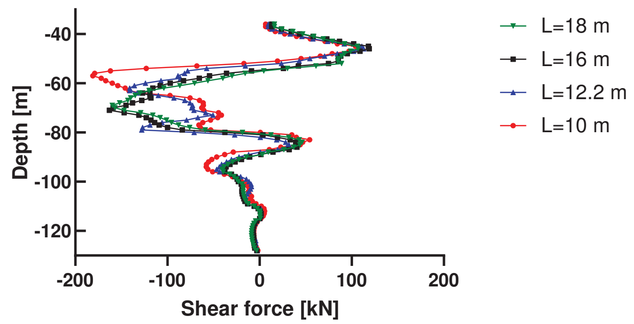

Fig. 6 The additional distribution of the shear forces of the monopiles

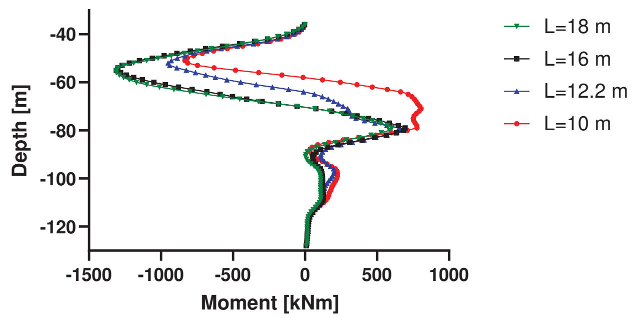

Fig. 7 The additional distribution of the moments of the monopiles

turbine generator good serviceability during the operation. The German standard uses 0.5° as the control value of the angular rotation of offshore wind turbines [8]. The Chinese standard defines the angular rotation at the mudline lower than 0.5° for monopile foundation, and angular rotation at the foundation top lower than 0.5° for other types of foundation [3]. The angular rotation lower than 0.5° at the top of the jacket platform was employed as the design criteria.

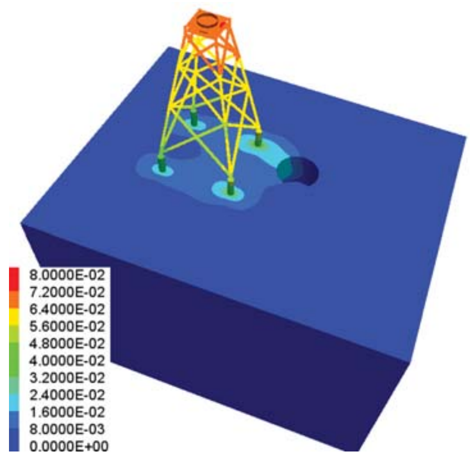

Fig. 8 The deformation contour for the case: a pockmark 12.2 m away from the jacket platform

Fig. 8 represents the deformation contour of the jacket platform located 12.2 m away from the pockmark induced by the spudcan penetration. Note that the distance between the jacket platform and the jack-up rig was applied in situ. The contour indicates that the maximum displacement at the top of the platform is approximately 80 mm. The angular rotation is about 0.06° much lower than the design criteria.

IV. CONCLUSION

The simulations were conducted with simplification in the program $FLAC3D$. The jacket platform with pile foundations was subjected to the structural loads from the wind turbine generator, the wind loads acting on the wind turbine, and the wave forces acting on the jacket platform. The pockmark, equivalent to the spudcan penetration, located near the jacket platform had less influences on the ultimate bearing capacity. However, the displacement was larger when the distance was lower. The maximum shear force and moment of pile occurred solely in the shallow soil layer. They were also larger when the distance was lower. The jacket platform with pile foundations performed well under marine conditions. The maximum displacement was approximately 80 mm, and the angular rotation was about $0.06°$ satisfying the design criteria.

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