Pile-soil Interaction Impact on Dynamic Response of Offshore Wind Tower Founded on Monopoles

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Keywords: Large Offshore Wind Turbine Founded on Monopole, *M* Method, *P-y* Curve Method, Solid Element Method, Wind Vibration Analysis.

Abstract. *M* method adopted in Chinese code is linear elastic subgrade reaction method, while the pile-soil interaction is extremely complex process and with greater limitations. *P-y* curve method is used to calculate the pile foundation; solid element method and monitoring results were compared and analyzed. The results showed that: natural frequency of the structure calculated in different method of pile foundation has a little effect, results are reasonable; in the wind vibration analysis of structure, *p-y* curve method and solid element method results are more consistent, it applicant to calculate in offshore wind turbine, the results are satisfactory; The applicability of *M* method under cyclic dynamic loads is studied in this article, when according to the specification values, using 3 ~ 4 times m value, the calculation result is more ideal.

Introduction

Offshore wind turbine foundation withstand the wind, waves and currents and the role of such loads, pile-soil interaction studies have been the focus and difficult of academic Commonly used methods of analysis of pile-soil interaction with *m* France and *p-y* curve method.

M method is simple in form, currently widely used as a linear elastic subgrade reaction method. Its biggest drawback is that take the foundation soil as an elastic body, ignored the nonlinear characteristics of the soil. In general the larger load level conditions or cyclic load, generally use plastic analysis model, where *p-y* curve method in engineering and academia widely used. This article use *p-y* curve method for pile foundation in tower foundation design, *m* method, *p-y* curve method calculation results are compared with the solid element method to examine the reasonableness of *p-y* curve method and analysis the *m* method. To provides some references for foundation design of the offshore wind turbine, and provide reference for same kind of ocean engineering.

Analysis Model and Parameter Determination

Project Overview

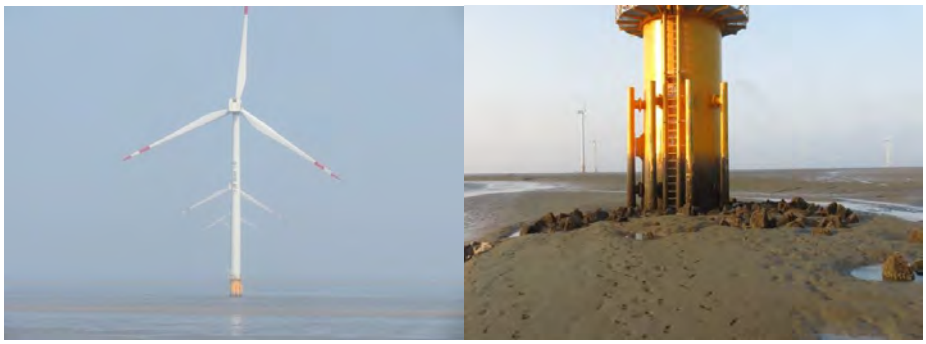

Fig. 1 Wind Turbine Site Conditions

Wind power station is area of intertidal away 14 Km from the coastline, the ground at Jiangsu Rudong and surface is mainly silt and relatively flat terrain. Capacity of WTG selected is 3.0 MW. Height of hub is 86 m, its pile foundation for the steel pipe piles, depth 39 m, thickness 60 mm, and wind turbine tower construction site conditions shown in Figure 1.

M Pile Interaction Simulation

Currently wind turbines foundation design mainly used a "wind turbine foundation design requirements" [1] (FD 003-2007) (hereinafter referred to as "wind code") m recommended method to calculate the ground resistance coefficient, in order to determine soil spring property, the finite element model diagram as shown in figure 2. Calculated the horizontal and vertical spring rate respectively by Equation (1) [2]:

$$C = m \bullet h \text{ , } k_s = b_0 \bullet \frac{C_{up} + C_{down}}{2} h_i \quad k_n = 0.5Uh\tau / \Delta \tag{1}$$

P-y curve Method for Modeling the Pile-soil Interaction

The so-called p-y curves, referring to the horizontal loads, a depth of under mud, curve relation between the horizontal reaction force and pile deflection. This will be based on the form of p-y curves given in DNV rules [3] to determine the properties of non-linear soil springs [4-10].

Soft clay under cyclic loading in the p-y curves were given in DNV rules, it can calculated according to equation (2) and Equation (3):

(1)For the case $X \le X_R$

$$\left.\begin{array}{ll} p = \frac{p_u}{2}\left(\frac{y}{y_c}\right)^{1/3} & y \le 3y_c \\ p = 0.72p_u\left(1-\left(1-\frac{X}{X_R}\right)\frac{y-3y_c}{12y_c}\right) & 3y_c < y \le 15y_c \\ p = 0.72p_u\frac{X}{X_u} & y > 15y_c \end{array}\right\} \tag{2}$$

(2)For the case $X > X_R$

$$\left.\begin{array}{ll} p = \frac{p_u}{2}\left(\frac{y}{y_c}\right)^{1/3} & y \le 3y_c \\ p = 0.72p_u & y > 3y_c \end{array}\right\} \tag{3}$$

Solid Element Method

To modeling the pile and soil, soil used Mohr materials to establish, pile foundation used three-dimensional shell to establish, set contact elements between the pile and the soil [11-13].To computational analysis the pile-soil interaction problems, the use of regional foundations to simulate infinite foundation, considering the infinite foundation radiation damping effect, we use dynamic viscoelastic artificial boundary conditions, and its high accuracy, can simulate the artificial boundary outside semi-infinite medium elastic recovery and good frequency stability, so the finite element analysis has been widely used in pile - foundation interaction.In the finite element simulation, achieving dynamic viscoelastic artificial boundary is applied, the normal and tangential respectively associated with the spring element and the damper required in the boundary nodes, corresponding expressions formula of spring K and damping coefficients C as follows, it can calculate for equation (4).

$$K = a\frac{\sum A_i G_i}{R} \text{ , } \quad C = \sum \rho_i c_i A_i \tag{4}$$

Where G_i is the shear modulus of artificial boundary nodes associated with the boundary element; P is the density of artificial boundary element associated with the boundary node; R is the distance for the scattering wave source to artificial boundary; C is the wave number of artificial boundary medium, C_p is the longitudinal wave velocity of normal damping, C_n is the shear wave velocity of tangential damping; values of a depend on the type of viscoelastic dynamic and setting artificial boundary orientation, for three-dimensional model, the tangential take 2/3 and normal take the 4/3; A_i is the area of artificial boundary nodes associated with the boundary cell.

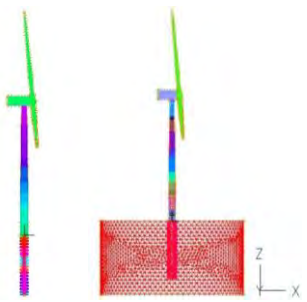

Fig. 2 FEM of M Method, P-y and Solid Element Method Curve

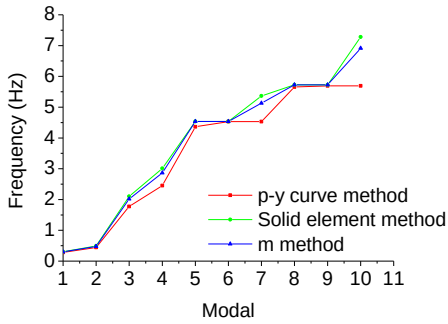

Fig. 3 Different Pile Interaction Calculation Methods for Wind Tower Dynamic characteristics

Dynamic Analysis of Wind Turbine

Dynamic characteristics Analysis of wind turbine is an important aspect fracture properties of structural, and important computational wind load parameters of structural, so this article were used different pile-soil interaction methods to analysis the dynamic characteristics of wind turbine tower structure, as shown in Figure 3, site monitoring structures were analyzed to verify the rationality of the model. As shown in Figure 3, the three methods of structural vibration frequency difference is small, results is reliable, three methods can be approximately calculated for the structural characteristics in general.

Wind Vibration Response Analysis of Wind Tower

Numerical Simulation of Wind Load

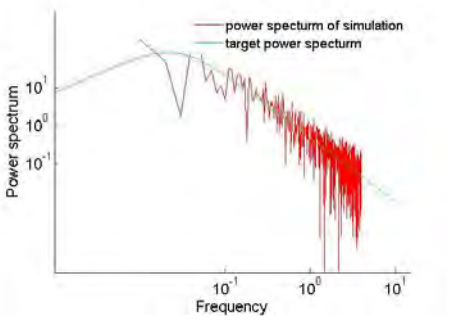

Fig. 4 Representative Spectrum of Fluctuating

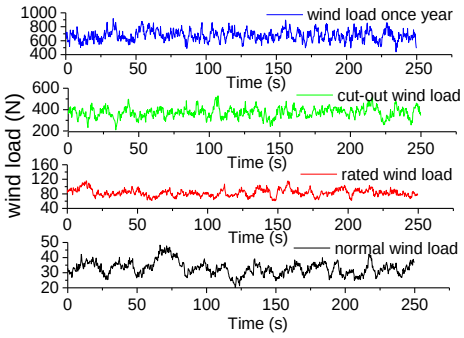

Fig. 5 Duration Curve of Wind Load

Rated wind speed of Wind turbine is, mean wind speed of represents annual of engineering field area at height 86m is $V_{ave} = 7.25\ m \cdot s^{-1}$, cut-out wind speed of Wind turbine is $V_{out} = 25\ m \cdot s^{-1}$,wind speed of 10 minutes average in 1 years is $V_{el} = 32.9\ m \cdot s^{-1}$. Based on the random vibration theory and norms of wind loads on wind load simulation, use the most representative and most reliable Davenport spectrum and using matlab, simulation wind load duration curve and considering the effects of fluctuating wind, cross-power spectral density function results with the target spectrum (Davenport spectrum) comparison

chart of fluctuating wind samples as shown in Figure 4. Seen form Figure 4, the sample spectrum of the wind using the regression model (AR) program to simulate fitting better with the Davenport spectrum.

Analysis of Computing Result

Loading applied of examples takes different wind speed loads on wind turbine tower. Under Load of the storm, displacement curves of the wind turbine pile top as shown in Figure 5. Under different wind speed, maximum displacement of wind turbine pile is shown in Figure 6~9.

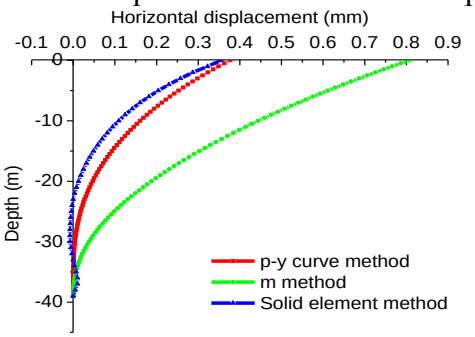

Fig. 6 Pile Displacement under Rated Wind Load

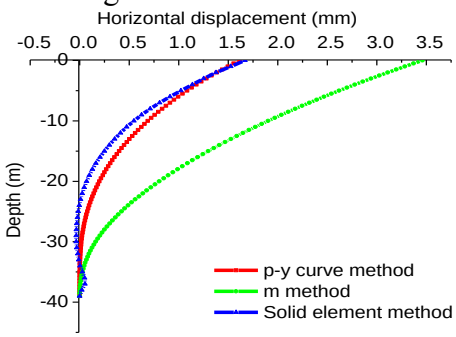

Fig. 7 Pile Displacement under Represents Annual Wind Load

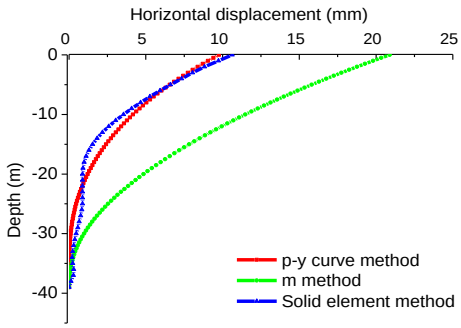

Fig. 8 Pile Displacement under Wind Load Once Year

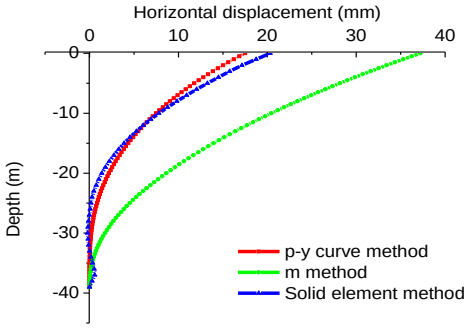

Fig. 9 Pile Displacement under Storm Load

Figure 6-9 show that the load is small, displacement calculated in p-y curve method is smaller than the soil surface solid element method calculation result, as the wind speed increases, p-y curve method to calculate the displacement of the soil surface than large solid element method, but when the storm loads, the result of p-y curve method calculated is smaller than solid element method, and displacement of plane mud calculated in m method larger than the previous two. The calculation of differences arising from factors: In extreme wind loads, especially when the storm loads, greater wind turbine vibration cause soil disturbance, reducing the soil stiffness, and p-y curve method simulate nonlinear spring, simulation is simplified approximation factor values, failure to consider the soil stiffness weaken, in addition, since geotechnical properties is extremely complicated, if only on the soil to determine the value of m form the class specification reference will cause calculated results actual large deviations.

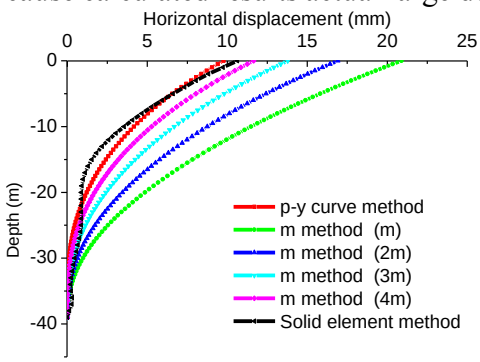

Fig. 10 Pile Displacement Comparison after Adjusted

Chinese code take m method for wind turbine pile foundation design, so in this article further study the applicability of m method, therefore appropriate adjustment scale factor of horizontal resistance coefficient in the m method, which is a measure of soil stiffness of the spring coefficients were used 2,3,4 times value of m, it is a case of maximum displacement distribution of pile under wind loads ones year shown in Figure 10.As shown in Figure 10, Value of m becomes larger, maximum displacement response of wind turbines pile foundation value decreases, when the value of m take four times m, displacement curves of the pile top is closer with p-y curve values, can be seen in the structure foundation design, if structure is subjected to repeated cycles of dynamic loads, when we do the analysis and design using the m method in Chinese Code , should be used 3m or 4m value , the calculation results were more desirable.

Summary

In summary, the following conclusions can be obtained:
(1) P-y curve method, solid element method and m method are calculated vibration die state of wind turbine tower structure that perform consistent, Although results of m method is different form the p-y curve method and the solid element method, the difference is less, results is reliable, three methods can be approximately calculated the characteristics of structural in general.
(2)M method is a linear elastic method, in the case of wind-induced vibration, soil experience in plastic state, and m method does not consider the nonlinear behavior of the soil, a large soil deformation around pile occurs, the soil must be considered nonlinear behavior of the effect on the pile body. For the wind, waves, earthquakes and other cyclic dynamic loads to calculated lateral deformation of the wind turbine pile foundation, when we use the m method to calculate the interaction of piles and soil, the m value must be properly adjusted, then the results will be reasonable.
(3) The solid element method can not only take into account the pile-soil interaction nonlinear behavior of the soil, but also consider the soil under cyclic loading in the repeated disturbance of the soil stiffness degradation effects, but its modeling more complex, unit is more computational efficiency is low, generally ,it is less used in the actual project, p-y curve method that is used with the small deformation analysis, also for large deformation analysis, and consider the wind, waves, earthquakes repeated loading effect. These features indicate p-y curve method is more suitable than m method in research pile foundation of offshore wind turbine, but it cannot consider the soil stiffness degradation, in future studies need to analyze the situation.

Acknowledgement

This work is supported by Natural Science Foundation of China (51178045) and Oversea Famous Teachers Project of Education department (MS2011BJKJ005).

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