Dynamic Analysis of a Tripod Offshore Wind Turbine under Earthquakes

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Abstract: Earthquakes are non-negligible hazards for the designing of offshore wind farms in the coastal regions of China, such as Bohai Bay. So, it is necessary to analyze the response of offshore wind turbines (OWTs) under earthquakes. Fluid mechanics are applied to the model, the interactions of sea water and the substructure are based on fluid theory analysis in this paper. Moreover, it takes into account of the influence of fluid-solid coupling effect, radiation effect of wave loads and pile-soil interactions on the OWT. By establishing the finite element model (FEM) and dynamic equation of a tripod OWT, the measured onshore and offshore seismic waves are applied in the finite element analysis of the Tripod OWT respectively, and the numerical analysis of a tripod OWT structure under different measured seismic waves is carried out. More detailed comparison of the differences between onshore and offshore seismic waves is carried out in the paper. The result shows that the offshore seismic waves stimulate more significant responses than the onshore one, which can be attributed to that abundant seismic frequencies are found around the fundamental frequencies of the OWT. The seismic response analysis is conservative by using the onshore seismic waves, however, using the offshore seismic waves is closer to the actual situation.

1. Introduction

In the past 30 years, with the development of offshore engineering in China, the field of engineering construction has made rapid progress, but the research on seismic performance of marine structures is slightly weak. Wind turbine power generation has been recognized as the main source of power supply in the world, wind technology has become a cutting-edge engineering technology, the number of OWTs is also growing. Because of the high cost and bad environment of OWTs, it is more susceptible to external loads, so it is necessary to perform seismic response analysis of OWTs under fluid-solid coupling effect. Under the earthquake, because the vibration of the structure will also produce a certain fluctuation of water, the surrounding flow field will also change, and the fluctuation will affect the structure again. This kind of fluctuation will not only change the dynamic characteristics of the wind turbine, but also directly apply the additional loads to the OWT foundation, which will further affect the dynamic response of the OWT, which is called the hydrodynamic pressure effect. Therefore, when studying the seismic performance of OWTs, it is necessary to consider the influence of hydrodynamic pressure. At present, some scholars at home and abroad have made certain achievements in the study of the influence of hydrodynamic pressure on seismic response of marine structures [1, 2]. The additional water quality analysis method based on Morison equation has been
widely used [3-5]. However, the disadvantage of the research is that the numerical analysis is performed by the Morison equation which is simplified, and most of them do not take into account the influence of fluid-solid coupling effect. Zhou and Zhang [6] carried out fluid-solid coupling analysis of wind turbine through ANSYS Workbench, and modal analysis of the blade itself and the blade in wind field with or without rotation are carried out and compared. Li [7] studied the seismic response analysis of pile-soil-bridge structure system. Sessarego et al [8] presented a fast computing technique for wind turbine fluid-solid coupling. Cheng and Oh [9] performed the fluid-structure coupled analyses of 10kW wind turbine blades by means of the full coupling between CFD and CSD based finite element methods.

Pile-soil interaction is a typical nonlinear problem, and the influence of different soil layers is not the same. At present, there are two theoretical methods for the study of pile-soil interaction: theoretical analysis and experimental methods. The elastic theory method and shear displacement method represented by Poulos [10], Cooke et al [11] are the most classical theoretical analysis methods. Based on the above ideas, Nogami and Chen [12] divided each pile into several sections and considered the stratification characteristics of the soil to obtain a numerical calculation equation that greatly simplified the Mindlin formula integral. According to the group effect on ultimate lateral soil resistance, Chen [13] presented a numerical analysis which combines the infinite and finite element method. The construction process of pile-supported pier was simulated by a plane finite element method (FEM) with an elasto-plastic constitutive relation of soil by Xie [14]. The horizontal displacement in front of pier and distribution of axial force and moment of piles were studied. Song [15] proposed an optimum design model for the offshore jacket platform considering multi-design criteria, multi-design constraints and the structure-pile-soil interaction.

2. Analysis methods of interaction between fluid and structure

2.1 Basic hydrodynamic equations

The motion of the fluid must satisfy the principle of conservation of mass [16], that is, in any selected geometry space, the mass of fluid flowing through the spatial boundary into space within a unit of time is equal to the increased fluid mass in this space. According to the principle of mass conservation, the general form of continuous equation is:

$$\frac{\partial \rho}{\partial t} + \nabla (\rho \ddot{u}) = 0$$

(1)

where $\rho$ is the density of the fluid; $\ddot{u}$ is the velocity of the fluid particle.

The ideal fluid assumes that the fluid is incompressible and non-rotating, then the continuous equation is:

$$\frac{d \rho}{dt} = 0; \quad \nabla \Phi = \ddot{u}$$

(2)

$$\nabla \cdot (\nabla \Phi) = 0$$

(3)

in which $\Phi$ is the fluid velocity potential.

Then, Laplace equation:

$$\nabla^2 \Phi = \frac{\partial^2 \Phi}{\partial x^2} + \frac{\partial^2 \Phi}{\partial y^2} + \frac{\partial^2 \Phi}{\partial z^2} = 0$$

(4)

The equation of motion for ideal fluid is:

$$\frac{\partial \Phi}{\partial t} + \frac{1}{2} (\nabla \Phi) \cdot (\nabla \Phi) + \frac{p}{\rho} + gz = 0$$

(5)
Usually solving the wave problem is first obtained $\Phi$ by the corresponding boundary condition and formula (4). Then the velocity of the fluid particle $\dot{u}$ is calculated by the formula (2), Finally, the pressure field $P$ is obtained by the formula (5).

2.2 Motion equations of structural systems

In the analysis of the dynamic response of OWTs under earthquakes, the interaction between the tripod foundation structure and the surrounding water needs to be considered. For the fluid-solid coupling problem of slender structures, the finite element theory is used to discretize the structure to obtain the equation of motion of the element. Then the equations of motion are combined into the whole structure. The motion equation of a structure under the earthquakes and fluids:

$$[M]\ddot{u} + [C]\dot{u} + [K]u + f_p + f_g = 0$$  \hspace{1cm} (6)

where $[M]$, $[C]$, $[K]$ are the mass matrix, stiffness matrix and damping matrix of the cylinder structure, respectively; $f_p$ is hydrodynamic pressure on a fluid-solid coupling interface; $f_g$ is earthquake action.

2.3 Radiation wave theory

Assuming that the initial state of the fluid is stationary, the vibration of the structure will result in the radiation of waves outward from the center of the structure. If the resulting wave is a small amplitude wave, it is considered that the interaction between the structure and the wave is linear and can be superimposed. When the time Parameter is separated separately, the radiation wave velocity potential at any point is:

$$(x, y, z, t) = (x, y, z)e^{-\text{i}\omega t}$$  \hspace{1cm} (7)

where $\phi(x, y, z, t)$ is suitable for Laplace equation:

$$\nabla^2 \phi = 0$$  \hspace{1cm} (8)

When $z=-d$:

$$\frac{\partial \phi}{\partial z} = 0$$  \hspace{1cm} (9)

When $z=0$:

$$\frac{\partial \phi}{\partial z} - \delta \phi = 0$$  \hspace{1cm} (10)

where $\delta = \frac{\omega^2}{g}$.

In addition, the normal acceleration of structures and the fluid particle of the structural surface is the same.

$$\frac{\partial \phi}{\partial \vec{n}} = \dot{u}_n$$  \hspace{1cm} (11)

where $\dot{u}_n$ is the normal acceleration of the structure; The direction of $\vec{n}$ is perpendicular to the surface of the structure; $\vec{n}$ is a unit vector.

When the radiation wave propagates to an infinite distance, the boundary condition can be established according to the Sommerfeld radiation condition [17]:

$$\lim_{r \to \infty} \sqrt{r} \left( \frac{\partial \phi}{\partial r} - i k \phi \right) = 0$$  \hspace{1cm} (12)
3. Hydrodynamic pressure induced by earthquake

3.1 Morison equation and fluid-solid coupling model

Morison equation is a semi-empirical semi-theoretical formula, which is applied to the structural response analysis of small-diameter piles under the action of regular waves. The basic assumption of the equation is that the existence of the pile or pier does not affect the movement of the fluid, and the velocity and acceleration of the waves can still be considered according to the original wave scale and calculated by the proposed wave theory. The full wave force expression based on the Morison equation is:

\[ f = \rho A \ddot{u} + C_m \rho A [\ddot{u} - \ddot{x}] + C_D \frac{\rho}{2} A [\ddot{u} - \ddot{x}] |\ddot{u} - \ddot{x}| \] \hspace{1cm} (13)

Assuming that \( C_M = 1 + C_m \), then the wave force can be further expressed as:

\[ f = C_M \rho A \ddot{u} - C_m \rho A \ddot{x} + C_D \frac{\rho}{2} A [\ddot{u} - \ddot{x}] |\ddot{u} - \ddot{x}| \] \hspace{1cm} (14)

where \( \rho \) is density of water, \( A \) is the projected area of the unit cylinder perpendicular to the wave direction; \( V \) is the volume of the underwater part of the unit cylinder; \( C_M \) is the dynamic water inertia coefficient; \( C_m \) is the added mass coefficient; \( C_D \) is the coefficient of drag force; \( \ddot{u} \) and \( \ddot{\ddot{u}} \) are the horizontal velocity and horizontal acceleration of the wave water particles at the center of the cylinder axis, respectively, which depending on the wave theory chosen; \( \ddot{x} \) and \( \ddot{\ddot{x}} \) are the relative velocity and relative acceleration of the cylinder, respectively.

3.1.1 Nonlinear Morison equation considering fluid-solid coupling effect. For the circular section foundation with a diameter of \( D \), assuming that the direction of movement of the cylinder is consistent with the direction of the wave motion, the Morison equation of the unit cylinder in this case can be expressed as:

\[ f = C_M \rho A \ddot{u} - C_m \rho A \ddot{x} + C_D \frac{\rho}{2} D [\ddot{u} - \ddot{x}] |\ddot{u} - \ddot{x}| \] \hspace{1cm} (15)

where \( D \) is diameter of the cylindrical foundation.

Obviously, it can be seen from equation (15) that the process of the wave and the foundation of the OWT takes into account both the fluid additive mass effect and the fluid-solid coupling effect; it can be seen as a complete wave force expression under various factors.

3.1.2 Linearized Morison equation considering fluid-solid coupling effect. Since the resistance term of the Morison equation is nonlinear, it will inevitably bring difficulties to the specific calculation in the actual analysis. Therefore, in order to simplify the calculation, most studies usually linearize the nonlinear damping term in the Morison equation to obtain linearization.

Wave force expression:

\[ f = C_M \rho A \ddot{u} - C_m \rho A \ddot{x} + C_D \frac{\rho}{2} A \sigma_{u-x} \frac{\sqrt{\pi}}{8} (\ddot{u} - \ddot{x}) \] \hspace{1cm} (16)

where \( \sigma_{u-x} \) is the standard deviation for relative velocity. Obviously, in the Wave Force formula (16), considering the relative velocity of the foundation and the fluid, the fluid-solid coupling effect is also
taken into account when using the Wave Force formula to establish the foundation-water dynamic equilibrium equation.

### 3.2 Calculation of earthquake hydrodynamic pressure on group piles

Radiation wave force is a very important issue in offshore structure. The complexity of the problem is that it is difficult to accurately determine the velocity of fluid radiation around the object and the phenomenon of fluid separation. The dynamic response analysis of the tripod OWTs under the offshore earthquake needs to consider the interaction between the underwater pile foundation and the surrounding water. In the actual situation, there is still a mutual influence between the pile cap and the pile group through the fluctuation of the water. Considering the mutual influence, the interaction between the structure and the water is more accurate. Based on the basic structure of the tripod OWT, this paper simulates the hydrodynamic pressure of the pile group.

At present, the research on the hydrodynamic pressure of group piles is still only in the theoretical stage, and the actual engineering test results are lacking. The hydrodynamic pressure for the pile group structure includes the interference and shadowing effects of adjacent piles. The Morison equation indicates whether the incident wave or the hydrodynamic pressure in the static water is caused by the relative motion between the structure and the water, and the two situations have the same mechanism. The formula for the hydrodynamic pressure $f_{gh}$ acting on the unit height of the entire pile is as follows:

$$
f_{gh} = \sum_i k_g f_{hi} = \sum_i -k_g C_m \rho \frac{\pi}{4} \dot{x} + \frac{1}{2} k_g C_D \rho D_i \dot{x} |\dot{x}| \tag{17}
$$

where $f_{hi}$ is the horizontal earthquake hydrodynamic pressure on the unit height of the pile; $k_g$ is the group pile coefficients.

### 4. Pile-soil interaction

Pile-soil interaction of offshore structures under earthquakes is a factor that must be considered. The selection of calculation model constraints and the determination of parameters directly affect the accuracy of numerical simulation. In this paper, the most popular composite foundation reaction method is $p-y$ curve [18] which is used for simulation calculation. The elastic foundation reaction method is adopted in the elastic zone of the soil layer, and the ultimate foundation reaction force method is adopted in the plastic zone of the soil layer. According to the continuous boundary conditions of the elastic zone and the plastic zone, the nonlinear relationship between the horizontal resistance and the displacement of the piles are obtained. Since the main vibration direction of the piled soil caused by the $x$-direction earthquake is horizontal, the vertical pile-soil interaction is neglected.

According to the East Sea of China where the OWT is located, the sea level is 0.06m, the average seabed position is -20.5m, and the seabed bedrock is -80.5m. According to the exploration results of the site measurement points combined with the geological data of the area, the $p-y$ curve parameter values of each soil layer can be obtained. The spring damping $c=4\rho v_s D$. Using the soil layer performance parameters to calculate the soil spring stiffness of the finite element model by $p-y$ curve method, the soil spring stiffness curve is obtained to simulate the pile-soil interaction.

### 5. Numerical simulation of the tripod OWT

#### 5.1. Finite element analysis model

The numerical simulation of the tripod OWT is based on the software Ansys. The model material is steel, and the bilinear follow-up model is adopted. The modules used in the model are mainly SHELL181 and MASS21. In dynamic analysis of the model, structural damping is Rayleigh damping. Mass of the blades, driven systems and generator are simplified as the concentrated mass at the top of tower in the FEM which is 238000kg. The finite element model of the OWT is shown in figure 1, and the detailed mesh of the OWT is shown in figure 2.
5.2 Loading of the finite element model
This study used typical measured earthquake. According to the seismic design specifications at home and abroad, the onshore seismic waves select the El Centro seismic wave with rich low-frequency components; the offshore seismic waves select the Pacific offshore seismic waves measured by the SMES detection station in 1990. The seismic waves vibrate in the x-direction of the model, and the orientation of the infrastructure is shown in figure 3. The seismic time history curve is shown in figures 4 and 5.
In order to research the dynamic characteristics and seismic response of OWTs, the simulation conditions mainly include onshore seismic waves and offshore seismic waves loading with different peak acceleration. The seismic analysis calculation conditions of the OWT is shown in table 1. The “W” represents a water state, and “N” represents a water-free state in table 1.

| Conditions | States | Seismic waves | EPA   |
|------------|--------|---------------|-------|
| 1.1        | N      | S3EE          | -     |
| 1.2        | N      | El Centro     | -     |
| 2.1        | W      | S3EE          | 0.05g |
| 2.2        | W      | S3EE          | 0.1g  |
| 2.3        | W      | S3EE          | 0.2g  |
| 3.1        | W      | El Centro     | 0.05g |
| 3.2        | W      | El Centro     | 0.1g  |
| 3.3        | W      | El Centro     | 0.2g  |

5.3 Dynamic analysis of the OWT under Earthquakes
The two seismic waves are analyzed in the first 30s. According to the time history curves, the peak acceleration of the offshore seismic waves appear at 6.9 s; the peak acceleration of the onshore seismic waves appear at 2.14s. At the moment when the peak acceleration occurs under working conditions 2.3 and 3.3, the dynamic characteristics of the tripod OWT structures are shown in figure 6 and 7. The maximum von Mises appears on the brace pole, and it is 20.5MPa. This shows that the strut joints at the bottom of the tower is more prone to stress concentration. And the minimum von Mises is not the same between these two seismic waves.
Figures 6-11 show the acceleration time history curve of the tower top, Flange and tower bottom of the OWT under the working conditions 2.3 and 3.3. For the high-rise structure of the OWT, the response is not only controlled by the first-order modal, but is mainly controlled by the one or two-order modal, so the top speed of the OWT is higher. According to the 2.3, 3.3 working conditions, the shape of the following diagrams are basically the same, and the peak acceleration is 0.2g. The acceleration response of the El Centro waves on the structure is significantly higher than that of the S3EE waves at the first four seconds, because the response of the onshore seismic waves are faster than the offshore seismic waves, generally. The effect of the offshore seismic waves are more obvious, and the structure is more likely to reach the yield failure. In figure 11, the acceleration at the top of the tower in the y direction perpendicular to the direction of earthquake is almost zero, but it cannot be ignored. The acceleration at the top of the tower in the y direction after 15s reaches stability quickly, and the acceleration at the top of the tower in the x direction reaches stability slowly. This is mainly due to the different effects of pile-soil interaction in both directions under earthquakes. Under the two kinds of earthquakes, the dynamic amplification coefficient along the wind turbine height distribution is obviously different. The main reason is that the seawater layer will affect the propagation process of the earthquake from the bottom along the structure upward, and due to the dynamic characteristics of the structure will form a certain amplification or reduction effect.
When studying the seismic response analysis of two earthquakes on structures, the internal forces at different locations of the structure are also different, as shown in figures 12 and 13. Therefore, this paper conducts a comparative study of offshore seismic waves at different locations of OWTs. The simulations were carried out using working conditions 2.1, 2.2 and 2.3. The internal force of the Flange simulated by different peak acceleration earthquakes is obviously larger than that of the tower top of the OWT. It can be seen that the Flange is the weakest part of the OWT. The larger the peak acceleration of the seismic wave, the less stable the internal force of the structure.

6. Conclusion
When a earthquake occurs in one of the sudden natural disasters, it will inevitably cause irreparable damage to the structure of the OWT. Therefore, based on the nonlinear Morison equation, this paper
considers the influence of hydrodynamic pressure on OWTs, and considers the interaction between pile and soil and fluid-solid coupling. The numerical analysis method is used to calculate the vibration response of wind turbine under different working conditions. So it can get the following conclusion:

(1) Considering the influence of the wave force, the acceleration and internal force of the structure are increased to varying degrees due to the effect of the additional mass force and the additional damping force of the water. Therefore, in the response analysis of the OWT, it is necessary to take into account the fluid-solid coupling effect and the additional mass effect, in order to facilitate the OWT structure design.

(2) The spectral characteristics of the input seismic waves and the intensity of the earthquake will have different effects on the hydrodynamic pressure effect of the structure; although the earthquake is random, it is necessary to select a reasonable seismic wave input for the site conditions of the structure as much as possible.

(3) The seismic response of the offshore earthquake and onshore earthquake are compared and analyzed respectively. It is found that there is a great difference between the offshore earthquake and the onshore earthquake, the simulation of the wind turbine structure by inputting onshore seismic waves is conservative, the use of offshore seismic waves is more accurate, and provides a theoretical basis for seismic response analysis of marine structures under the offshore earthquakes.

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References
[1] Arnold, P., Bea, R. G., Idriss, I. M., Reimer, R. B., Beebe, K. E., Marshall, P. W. (1977). A study of soil-pile-structure systems in severe earthquake. The Offshore Technology Conference, Houston, USA.
[2] Anthony, N. W. (1986). Earthquake response of submerged circular cylinder. Ocean Engineering, 13(6): 569-585.
[3] Suchithra, N., Koola, P. M. (1995). A study of wave impact on horizontal slabs. Ocean Engineering, 22(7): 687-697.
[4] Sundar, V., Vengatesan, V., Anandkumart, G., Schlenkhoff, A. (1998). Hydrodynamic coefficients for inclined cylinders. Ocean Engineering, 25: 277-294.
[5] Wolfram, J., Naghipour, M. (1999). On the estimation of Morision force coefficients and their predictive accuracy for very rough circular cylinders. Applied Ocean Research, 21: 311-328.
[6] Zhou, H., Zhang, Y. (2013). Fluid-solid coupling analysis of wind turbine blade based on ANSYS Workbench. Hebei Journal of Industrial Science and Technology, 30(5), 314-318.
[7] Li F. (2008). Seismic response analysis of water-pile-soil-bridge structure system. Journal of Water Resources and Architectural Engineering, 6(2): 47-52.
[8] Sessarego, N., Ramos-Garcia, W. Shen Z. (2015). Development of a fast fluid-structure coupling technique for wind Turbine computations. Journal of Power & Energy Engineering, 3(7): 1-6.
[9] Cheng, T. H., Oh, I. K. (2007). Fluid-structure coupled analyses of composite wind turbine blades. Advanced Materials Research, 26-28: 41-44.
[10] Poulos, H. G. (1973). Analysis of piles in soil undergoing lateral movement. Journal of the Soil Mechanics and Foundation Division, 99(5): 391-406.
[11] Cooke, R. W., Price, G., Tarr, K. (1979). A study of load transfer and settlement under working condition. Geotechnique, 29(2): 113-147.
[12] Nogami, T.,Chen, H. L. (1984). Simplified approach for axial pile group response analysis. Journal of Geotechnical Engineering, 110(9): 1239-1255.
[13] Chen, L., Poulos, H. G. (1993). Analysis of pile-soil interaction under lateral loading using infinite and finite elements. Computers and Geotechnics, 15(4), 189-220.
[14] Xie, X. Y., Huang, H. W., Zhang, D. M. (2006). Numerical modeling of pile-soil interaction in pile-supported pier of a harbor. Chinese Journal of Geotechnical Engineering, 28(6): 715-722.

[15] Song, Y. (1999). Optimum design of jacket platforms considering structure-pile-soil interaction. China Ocean Engineering, 13(3): 309-316.

[16] Wen, S., Yu, Z. (1991). Wave Theory and Computational Principles. Beijing: Social Science Press.

[17] Yan, Y. (1991). Ocean engineering wave mechanics. Tianjin: Tianjin University Press.

[18] America Petroleum Institute. (2000). Recommended practice for planning, designing and constructing fixed offshore platform-working stress design. Washington D.C., USA.