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Dynamic Analysis of Single Pile Wind Power Foundation Structure

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Abstract: The single pile offshore wind power foundation structure is the most widely used form of offshore wind power platform. The rotating frequency of the blade in the wind turbine has an important impact on the dynamic characteristics of the structure. The rule requires that the excitation frequency should avoid the natural frequency of the structure. In the numerical simulation, the pile-soil interaction is considered by applying boundary conditions. The typical foundation structures, single pile, is selected, to analyze the influence of different boundary conditions on the natural vibration characteristics of single pile offshore wind power foundation structure in ANSYS modal. And a simplified method of boundary conditions suitable for ANSYS modal analysis is proposed. The results show that the simplified boundary condition method proposed in this paper is suitable for modal analysis of single pile offshore wind power foundation structure.

Keywords: Fixed Offshore Wind Power Foundation; Pile-soil Interaction; Single-pile Platform; Modal Analysis.

1. Introduction

Unlike traditional offshore oil platforms, offshore wind turbines are designed as towering structures to improve the power generation efficiency. The high structure itself is flexible, and the fan blade vibrate under wind load, which may threaten the safety of the whole offshore wind power platform structure. Therefore, the dynamic characteristics of the offshore wind power platform structure must be analyzed. Dong Xiaofeng [1] from Tianjin University studied structural vibration response characteristics and regularities of a large offshore wind turbine main structure under different operating conditions, and discussed the key factors affecting the structural vibration of offshore wind turbines and their influence on the vibration safety of wind turbines. The results show that when offshore wind turbines are in operation, the impeller speed has obvious influence on the vibration of offshore fan structure, and the impeller speed plays a leading role in the vibration change of fan structure. Cao Guangqi [2] used ANSYS to analyze the natural vibration characteristics of the five-pile jacket offshore wind power foundation structure, and proved that blade sweep frequency and soil properties would affect the natural vibration characteristics of the structure. Li Yi [3] established several models with different parts of the three-pile foundation offshore wind power platform. Li Wei [4] used ANSYS finite element analysis software to establish the finite element model of the fixed offshore wind power foundation structure. P-y curve method, m method and the method of modeling the soil with solid elements were adopted to analyze the natural vibration characteristics of the structure, and the applicability and errors of the three methods were compared. The results show that the modal analysis of large diameter single pile offshore wind power foundation structure using P-y curve method will produce a large error, and the bearing capacity of soil in a certain depth range is easy to reach a high level, which will cause the design length of pile not meeting the requirements.

In this paper, ANSYS is used to establish a finite element model of a single pile offshore wind power foundation structure, and two boundary condition simplification methods which are widely used: fixed constraint applied at 6 times the pile diameter below the mud surface and the soil solid element modeling, are used to analyze the natural vibration characteristics of the structure. These two models are used as the reference model. An equivalent spring element method considering stiffness is proposed as a new boundary condition simplification method, and its analysis results are compared with those of two reference models to verify its applicability to single pile offshore wind power foundation structure.

2. Mechanism of Pile-soil Interaction

Pile foundation is a very important part of offshore platform, which is usually inserted into the seabed soil layer by driving, and the design depth is generally determined by the actual situation. Pile foundation can bear most of the load. For piles bearing vertical loads, the main resistance is pile side friction and pile end resistance. Because piles may pass through different soil layers after being driven into the foundation, the properties of soil layers and the size of piles will affect the vertical bearing capacity of piles. The lateral load borne by the pile body is transmitted to the lateral soil mass. Meanwhile, other forces borne by the soil mass will also be fed back to the pile body, and the resistance factor, flexural stiffness and strength on the side of the pile will affect the magnitude of the lateral bearing capacity. Therefore, in the process of analysis, it is necessary to pay attention to the interaction between pile and soil, which will directly affect the bearing capacity analysis of pile legs and even the bearing capacity analysis and safety assessment of the whole platform.

When the pile is subjected to horizontal load, the balance of horizontal load is mainly achieved by the resistance of the soil around the pile. As for the pile body, it will bear horizontal load and moment. Under these two forces, the pile body will have horizontal displacement and bending stress. The pile body can bear part of external forces, and the pile-soil contact surface can also bear part of external forces. Under the action of external forces, the soil mass will be deformed, and the soil mass will also have some resistance. When the external forces are small, the resistance of the soil can be considered to be in the linear elastic stage in the process of elastic compression. However, when the load is further increased, the force of the topsoil will increase, and then yield. At this time, the deeper soil layer begins to bear the external load. Therefore, under the action of horizontal load, part of soil exhibits elastic changes and the other part exhibits plastic changes, which makes the study of pile-soil interaction more complicated.

3. Dynamic Analysis of Single Pile Offshore Wind Power Foundation Structure

3.1. Principal Dimension of Structure

In this paper, the specific size and equivalent method of the single pile offshore fan tower are based on the data in Liu Chao [5] 's paper. The fan tower is 73.17m high, the section of the cylinder is changing, the mass and stiffness remain discontinuous, the maximum outside diameter is 4.3 m, and the minimum outside diameter is 3.25 m. The wall thickness varies discontinuously along the height of the tower. The maximum wall thickness is 0.05m and the minimum wall thickness is 0.028m.

The single pile offshore wind power foundation structure is simplified as follows:

(1) The fan tower is simplified into a structure whose outer diameter and wall thickness are unchanged along the height of the tower, and the simplification principle is to keep the total mass of the fan tower unchanged. The reduced outer diameter and reduced wall thickness are shown in Table 1.

Table 1. Reduced outer diameter and wall thickness

	Outer diameter (m)		**Wall thickness (m)**	
Original size	MAX	4.3	MAX	0.05
	MIN	3.25	MIN	0.028
Reduced size	4.028		0.0274	

(2) The bottom of the fan tower cylinder is connected to the deck, and the deck mass is 1000kg. The main scale of the offshore wind platform deck is small, so the deck is not modeled. The effect of the deck on the fan platform is simulated by applying mass points to the bottom of the fan tower cylinder.

(3) The top structure of the fan tower cylinder includes blades, engine room and other facilities, with a total mass of 166,755 kg. In the modeling, the top structure of the fan tower cylinder is applied to the top of the tower drum as the mass point.

According to the environmental conditions, considering the design high water level, maximum design wave height and air gap, the deck position should be located at least 10.304m above the sea level, and the deck position is located 15m above the horizontal level in this paper. The upper part of the deck is connected to the fan tower cylinder, and the lower part is connected to the single pile foundation.

Table 2. Material properties

Property	**Numeric value**
Density (kg/m^2)	7850
Elastic modulus (MPa)	206000
Poisson ratio	0.3

The whole single pile offshore wind power foundation structure uses DH36 high-strength Marine steel, and its material properties are shown in Table 2.

3.2. Times of the Pile Diameter Method

When ANSYS is used to analyze and solve marine structures, fixed constraints applied to the structure at 6 times the pile diameter below the mud surface are often used as the boundary condition. This method is called 6 times the pile diameter method.

A fixed constraint is applied to the source of a single pile offshore wind power foundation structure at 6 times the pile diameter below the mud surface, as shown in figure 1.

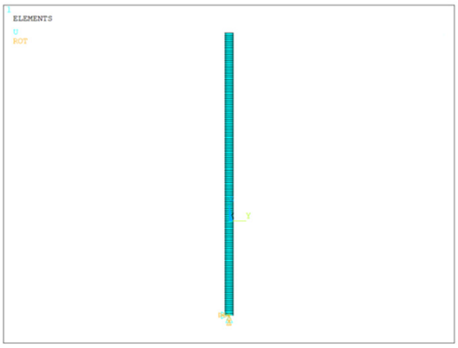

Figure 1. Single pile offshore wind power foundation structure with constraint

Through the modal analysis of the single pile offshore wind power foundation structure, the first 6-order natural frequency of the structure obtained is shown in Table 3.

Table 3. Natural frequency of single pile offshore wind power foundation structure with 6 times pile diameter method

Order	**Natural frequency (Hz)**
1	0.23114
2	0.23114
3	1.43455
4	1.43455
5	3.95624
6	3.95624

3.3. Solid Element Method

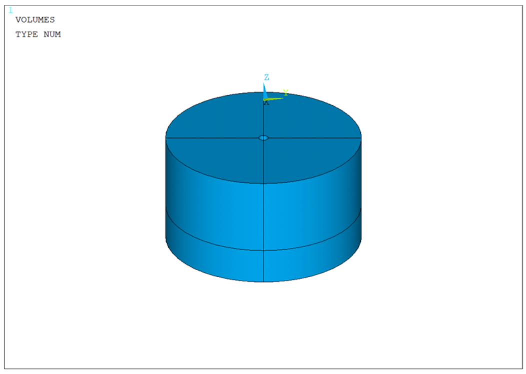

Figure 2. Solid model

The soil was modeled by the SOLID45 element in the ANSYS, and the seabed soil is silt, with deformation modulus of 13MPa, poisson ratio of 0.3, density of 1.95 g/cm^3, cohesion of 3 kPa, and internal friction angle of 23. Soil adopts DP model in ANSYS, and DP model is the ideal elastic-plastic model. In the simulation, three parameters are essential if the DP model is used, the first is the cohesion *c*, the second is the internal friction angle, and the third is the expansion angle. In the process of using this model for analysis, the expansion angle of the general soil should be set to 0 [6]. The soil range is 10 times the pile diameter, that is, the radius of the cylindrical soil is 40.28m and the height is 50m. Fixed constraints are imposed on the side and bottom of the cylindrical soil, with a free surface at the top. The soil model is shown in Figure 2, The FEM model is shown in Figure 3.

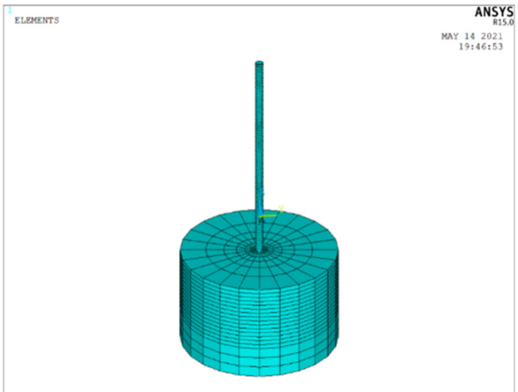

Figure 3. Finite element model of single pile offshore wind power foundation structure based on solid element method

The soil is modeled and solved by SOLID45 solid element in ANSYS, and the first 6-order natural frequency is shown in Table 4.

Table 4. Natural frequency of single pile offshore wind power foundation structure with Solid element method

Order	Natural frequency (Hz)
1	0.20032
2	0.20032
3	1.24486
4	1.24486
5	3.43980
6	3.43980

3.4. Equivalent Spring Element Method

The equivalent spring element method is a method to simplify the soil to equivalent spring applied on the structure. Since modal analysis in ANSYS will ignore nonlinear features, COMBIN14 elements are used to simulate the effect of soil on the structure. The real constant of COMBIN14 element includes the spring stiffness and damping. The damping of the soil is selected according to the empirical data. The damping is 0.03 in this paper, and the horizontal bed coefficient is calculated and analyzed. In the calculation process of the coefficient, it is necessary to combine the standard number of penetration hits, and the corresponding empirical formula [7] as follows:

$$k=0.2N.\ (kgf/cm^3 \text{ or } 10N / cm^3)$$

The standard number of penetration hits of silt is 7, and the horizontal bed coefficient is $14N / cm^3$. The pile length of the single pile offshore wind power foundation structure is 34m, and the spring element is set every 1m below the mud surface. The spring length is 1m, and the stiffness is the product of the area and the horizontal bed coefficient. According to the projected area of the pile in the plane within a height of 1m, the stiffness can be calculated to be 1.12784×10^8N/m.

Through the modal analysis of single pile offshore wind power foundation structure, the first 6-order natural frequency obtained is shown in Table 5.

Table 5. Natural frequency of single pile offshore wind power foundation structure with equivalent spring element method

Order	Natural frequency (Hz)
1	0.20020
2	0.20032
3	1.24351
4	1.24486
5	3.43653
6	3.43980

3.5. Error Analysis

The 6 times pile diameter method is a common method to simplify the boundary conditions of the offshore fixed pile structure, while the solid element method is more accurate in theory. Therefore, the 6 times pile diameter method and the solid element method are used as the benchmark to analyze the error of the equivalent spring element method. The error analysis based on 6 times pile diameter method is shown in Table 6 and that based on solid element method is shown in Table 7.

Table 6. Error analysis of natural frequency based on 6 times pile diameter method

Order	Natural frequency (Hz)
1	13.4%
2	13.3%
3	13.3%
4	13.2%
5	13.1%
6	13.1%

Table 7. Error analysis of natural frequency based on solid element method

Order	Natural frequency (Hz)
1	0.06%
2	0%
3	0.11%
4	0%
5	0.10%
6	0%

According to the figures in Table 6 and Table 7, when the natural vibration frequency of the single pile offshore wind power foundation structure calculated by the 6 times of the pile diameter method is used as the reference, the error of the equivalent spring element method is about 13%, and the error of the natural vibration frequency of each order is basically the same, and all are within the acceptable range. The error of the equivalent spring element method is almost 0 when the natural frequency calculated by the solid element method is taken as the reference. By analyzing the error of natural vibration frequency calculated by the three methods, the following conclusions can be drawn:

(1) Compared with the two reference models, the error of natural vibration frequency calculated by the equivalent element spring method is within the acceptable range. The equivalent spring method can be used to simplify the boundary conditions in the modal analysis of single pile offshore fan foundation.

(2) Both equivalent spring element method and solid element method consider the physical and mechanical properties of soil, which cause a small error, indicating that the mechanical properties of soil should be measured and analyzed in practical engineering for accuracy.

4. Conclusion

The vibration characteristic of single pile offshore wind foundation structure has great influence on structure design and check. Thus, considering the mechanism of pile-soil interaction of offshore wind platform, the equivalent spring element method used as boundary condition is proposed in this paper. And the method is compared with the commonly used boundary conditions simplification method. verified the applicability of the method for single pile wind power foundation structure. The specific conclusions obtained are as follows:

The error of the natural vibration frequency calculated by the equivalent spring element method of single pile foundation is very small compared with results by the solid element method. The equivalent spring method can be used as a boundary condition simplification method in the modal analysis of single pile offshore wind power foundation.

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