

Natural frequency and vibration analysis of jacket type foundation for offshore wind power

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Abstract. There are various types of foundation structure for offshore wind power, engineers may assess the condition of ocean at wind farm, and arrange the transportation, installation of each structure members, furthermore, considering the ability of manufacture steel structure as well, then make an optimum design. To design jacket offshore structure, unlike onshore cases, offshore structure also need to estimate the wave excitation effect. The aim of this paper is to study the difference of natural frequency between different kinds of structural stiffness and discuss the effect of different setting of boundary condition during analysis, besides, compare this value with the natural frequency of sea wave, in order to avoid the resonance effect. In this paper, the finite element analysis software ABAQUS is used to model and analyze the natural vibration behavior of the jacket structure.

1. Introduction

The offshore wind energy plays an important role in green power industries, therefore lots of countries engage in this field. Building offshore wind farm is not only the task of power industry but also includes civil engineering, material engineering and marine engineering. Due to the large scope, each detail and risk should be concerned.

To construct offshore wind farm is much more difficult than onshore condition, so the structural design should concern the strength and the feasibility of construction. But most of offshore structures are huge, it is very difficult to carry out the real scale test. Computer-aided engineering is a way to help engineer to simulate and arrange their design. Natural vibration frequency is an important index among the structural strength and integrity. The boundary conditions, including the effect of soil structure interaction may affect the behavior of vibration a lot. Most of the models may simplify the boundary condition between soil and structure to fixed end, because the stiffness of soil is very complicated to describe, but the fixed end assumption may be unconservative in soft soil conditions. This study uses finite element software ABAQUS to analyze natural frequency, and adopt spring elements to simulate soil condition and simplify the problem.



2. Parameters

The piles under each legs of jacket foundation are installed by pre-piling method, the connecting method between leg and pile may be different from post-piling type. The diameter and length of the pile may be considered by the bearing capacity of soil, in addition, the distance between the bottom of legs also need to be considered by the stability of overturning.

The size of the model in this paper is refer to the design for the offshore wind field in Taiwan Strait, and some parameters are reasonably assumed if they are not available. The site is set at the sea area of 30 m water depth. In order to avoid the action force of waves to disturb the transition piece and tower, the height of the jacket needs to exceed the depth of sea and also reserve the air gap.

According to the products and previous cases [1], the tower height of 6 MW wind turbine is about 90 m to 140 m, this paper assumes the tower height is 110 m. The simulation of seabed is using the parameters from Taiwan Power Company which is obtained by drilling test at the wind field in Taiwan Strait. Integrated above items and refer to some real design, the size, material and soil condition (Table 1) are as follows:

Structure Scale

Jacket Height : 50.0 m
Jacket Upper Width : 8.0 m
Jacket Footprint Width : 20.0 m
Pile Diameter : 2.0 m
Pile Length : 40.0 m
Tower Height : 110.0 m
Rotor & Nacelle Mass : 400.0 t

Material

Steel Density : 7.85 t/m³
Steel Elastic Modulus : 210.0 GPa
Poisson ratio : 0.3
Concrete Density : 2.4 t/m³

Table 1. Soil Parameters

Depth (m)	Description	γ_t (t/m ³)	c (t/m ²)	ϕ' (deg.)
0.00 ~ 21.5	SM	1.93	4.98	27.6
21.5 ~ 24.5	SC	1.95	14.9	--
24.5 ~ 31.25	SM	1.91	--	38.3
31.25 ~ 33.45	CL, SC	1.97	12.1	--
33.45 ~ 35.75	SM	2.01	--	40.5
35.75 ~ 39.75	ML	1.89	13.1	--
39.75 ~ 44.00	SP-SM	1.98	--	43.5

3. Model establishment

3.1. Comparison against a reference study

In this paper, the model is established by finite element software ABAQUS. Because the mechanical behavior of each members in jacket structure is close to beam element, besides, due to jacket structure includes a lot of connecting part, and the setting for those connection may concern with the contact behavior between each members, these setting may spend much more operation times, and also increase the difficulties to get convergent result. In order to simplify the problem, beam element is used to build piles, tower and the members in jacket structures.

In the first part of this analysis, a comparative model is built as a reference, the natural frequency of this comparative model was already analyzed by other researchers by using the finite element software like ANSYS and SubDyn [2], and the model is shown in Figure 1. By comparing the value of natural frequency computed by ABAQUS with the reference article [2], the accuracy of this analysis and all the modeling steps are assured.

In this study, only the foundation part is considered, including jacket and part of piles (5 meters length), the boundary condition is to fix all degree of freedom at the bottom of piles as Figure 2 shows.

The result from reference article [2] is shown in Table 2 and Figure 3. After analysis, the natural frequency of first eight modes extracted from ABAQUS. By comparing the result between corresponding modes, the value and tendency are very similar, that means this modeling method and analytic step is workable.

Table 2. Natural frequency (Cycles/sec.)

Mode	1 st Mode	2 nd Mode	3 rd Mode	4 th Mode
ABAQUS	2.0831	2.0831	5.1435	5.3890
References	2.5500	2.5500	5.0500	7.5000
Mode	5 th Mode	6 th Mode	7 th Mode	8 th Mode
ABAQUS	7.4018	7.4018	7.6830	7.9759
References	7.5500	7.5500	8.5000	9.0500

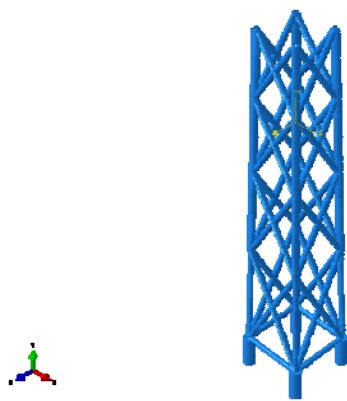


Figure 1. Jacket structure model of control group

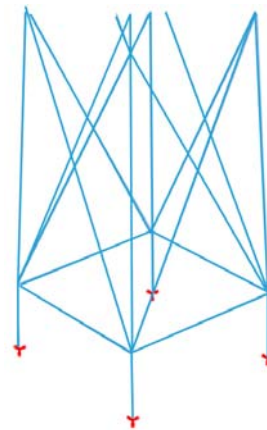


Figure 2. Fixed boundary condition of control group

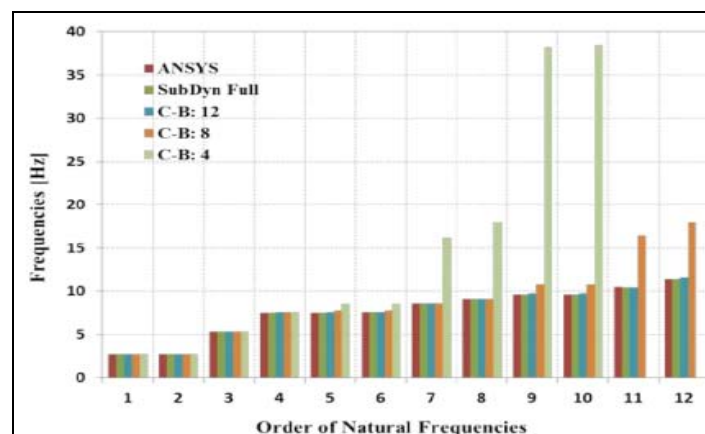


Figure 3. Natural frequency [2]

3.2. Boundary Condition and Pile-Soil Interaction Study

The following study analyzes the natural frequency in two conditions, one is the boundary surface around pile fixed, and the other case includes soil effect.

With the parameters of model described previously, besides, the mass of rotor nacelle assembly is assumed as a concentrated mass point on the top of tower whose arrangement of the model is shown in Figure 4.

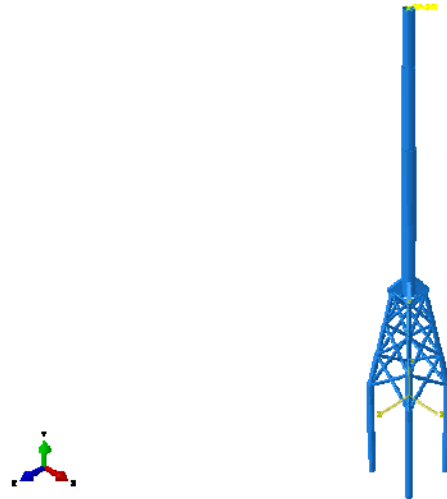
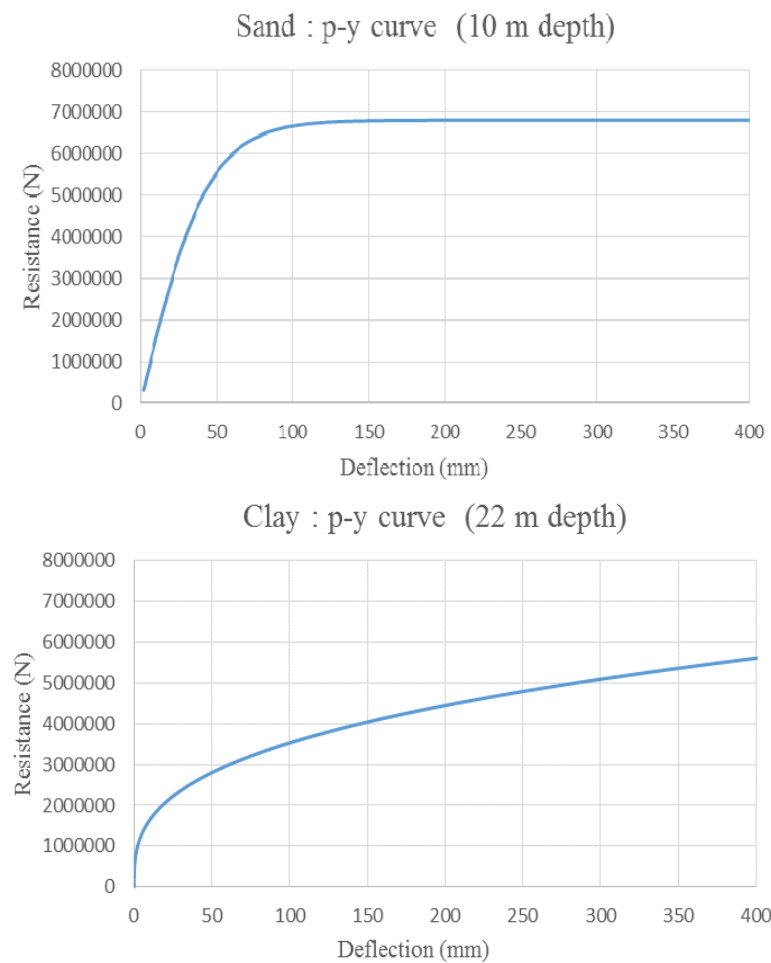
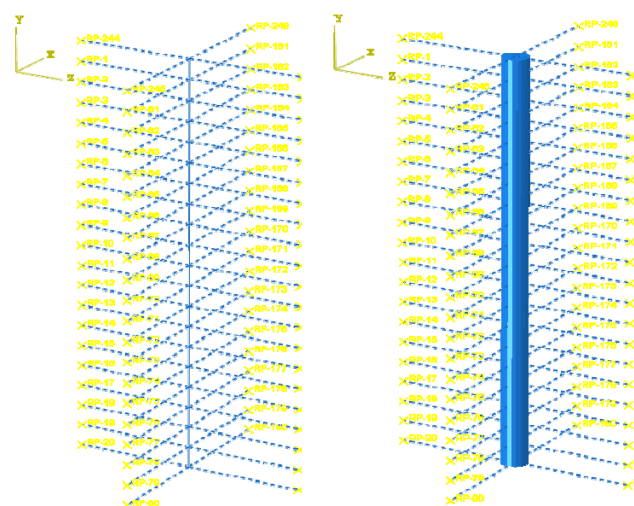


Figure 4. Jacket structure model

For the purpose of simulating the interaction between soil and pile structure, the empirical formulas for p-y curve provided by API (American Petroleum Institute) [3] are used to display the stiffness behavior of soil around piles. With the empirical formulas and soil parameters of offshore wind field show in Table 1, the soil spring with non-linear stiffness, which is the resistance-deflection relationship of the soil, can be simulated. The relationship between lateral bearing capacity and lateral deflection of soil may different along with the depth, for this reason the p-y curves corresponding to each depth need to be calculated one by one, Figure 5 shows the p-y curve of sand in 10 m depth and p-y curve of clay in 22 m depth.

The pile length penetrating into seabed is 40 m, and the spacing between soil springs is 2 m, so there will have 21 different stiffness soil springs per pile in one direction. For the soil characteristic that only taking compression, the nonlinear elastic property of each spring is only input the compression part, so it will need four springs on x-z plane to provide lateral support, the arrangement of soil springs around pile is shown in Figure 6. However, the friction force on the lateral surface of pile is ignored, so the degree of freedom in vertical direction (y direction) is set to free, but at the bottom of pile is set to fixed, in order to support the structure and simplify the model.

During analysis, first eight modes from fixed pile model and soil spring model are extracted, and compared with each other. As the result shown in Table 3 indicates, the deformation tendency of both models are similar, but the values from soil spring model are a little bit smaller than the values from fix-pile model, the reason of this phenomenon may be the stiffness of soil-spring must smaller than fixed boundary, so the structural behavior of soil-spring model may be more flexible, and the corresponding natural vibration period will be longer.

**Figure 5. P-y curve****Figure 6. Soil-spring around pile**

Furthermore, applying a cyclic load which the amplitude is 100 kN on the top of jacket for 50 sec with the load frequency equals to the value of first mode of structure, in order to check the response of structure, and also test others load frequency to compare, including 0.1, 0.15, 0.25, 0.3, 0.4 (Hz).

Figure 7 shows the displacement of tower tip over time when the load frequency is equal to the natural frequency, the tendency is getting divergent, means resonance phenomenon occurs. The results of maximum displacement at tower tip in each above cases are shown on the graph in Figure 8. The outcome clearly shows that the structural response will increase obviously if the load frequency is close to the structural natural frequency.

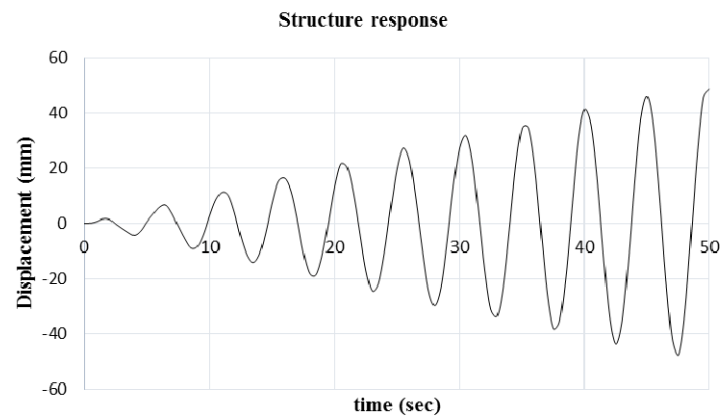
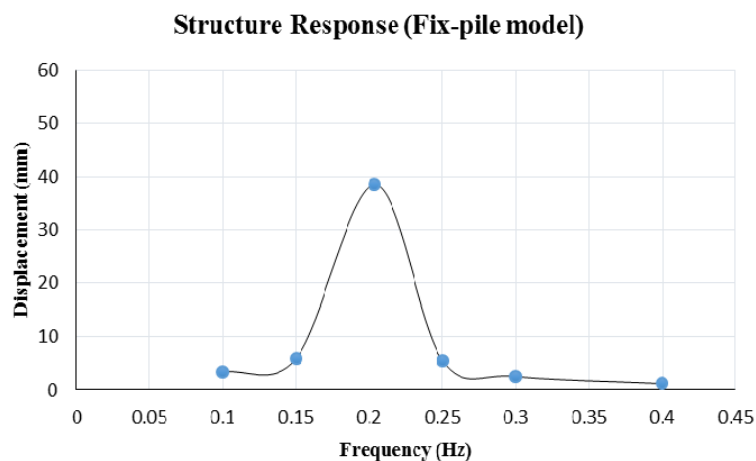


Figure 7. Resonance response

Table 3. Natural frequency (cycles/sec)

Mode	1 st Mode	2 nd Mode	3 rd Mode	4 th Mode
Fix-pile model	0.2038	0.2038	1.4459	1.4459
Mode	1 st Mode	2 nd Mode	3 rd Mode	4 th Mode
Soil-spring model	0.2036	0.2036	1.4109	1.4110
Mode	5 th Mode	6 th Mode	7 th Mode	8 th Mode
Fix-pile model	3.4334	3.4334	4.3930	5.5029
Mode	5 th Mode	6 th Mode	7 th Mode	8 th Mode
Soil-spring model	2.8968	2.8968	4.2362	4.4512



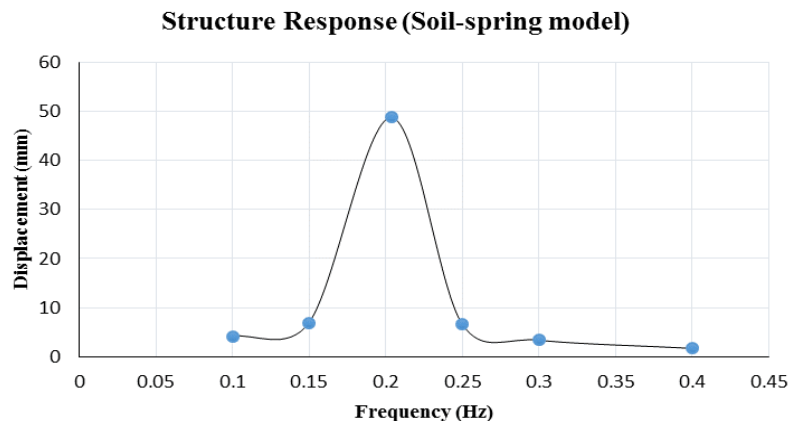


Figure 8. Structure response

3.3. Advanced Apply

Comparing the structural frequency from previous analysis to the probability about the significant wave height and the corresponding mean period at one of wind farms in Taiwan Strait (in Appendix A), the natural frequency is in the region of high occurrence rate of wave frequency. In order to avoid resonance occur, the mass or stiffness of structure need to be modified

First, after comparing to other jacket structures, a mud-brace is added at the bottom of jacket, and the difference of natural frequency is observed. From the result shown in Table 4, the value has increased a small amount, but it is still not enough to improve the whole structure.

The other approach is to decrease the tower height to 90 m, from the result in Table 5, the natural frequency has changed obviously. These two approaches and the simulation in last section are in purpose to figure out the effect of different members in structure. In reality, engineer may consider the requirement and condition, and design the structure cautiously.

Table 4. Natural frequency (Structure with mud brace)

Mode	1 st Mode	2 nd Mode	3 rd Mode	4 th Mode
Freq. (cycles/sec)	0.2040	0.2040	1.4328	1.4328

Table 5. Natural frequency (Structure with 90 meters tower height)

Mode	1 st Mode	2 nd Mode	3 rd Mode	4 th Mode
Freq. (cycles/sec)	0.3048	0.3048	2.2564	2.2564

4. Conclusions

For the result of this study, the method of soil spring can present the deformation behavior of soil without build the soil element. In addition, the mode shape of high frequency showed existence of different behavior between these two models. In real environment condition, the seabed cannot provide perfect fixed restraint, especially in shallow region, the capability of lateral support from soil is lower at the shallow part than deeper part, so in this situation the fixed boundary setting will be unreal.

Once the foundation design requires pile-soil interaction calculation, soil spring method can save a lot of computational resource and easy to get convergent result. In order to simplify the problem, the friction force on the surface between pile and soil are ignored. Future studies should consider the soil spring in vertical direction, and the behavior of structure will be more accurate.

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Appendix A Joint probability of wave heights and periods

T_m (sec)	$H_{1/3}$ (m)											Total
	0.0~0.5	0.5~1.0	1.0~1.5	1.5~2.0	2.0~2.5	2.5~3.0	3.0~3.5	3.5~4.0	4.0~4.5	4.5~5.0	>=5	
0~1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1~2	0.55	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.55
2~3	8.28	0.08	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	8.37
3~4	6.03	11.23	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	17.26
4~5	0.37	13.87	8.53	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	22.77
5~6	0.01	2.20	8.96	8.07	0.07	0.00	0.00	0.00	0.00	0.00	0.00	19.30
6~7	0.00	0.21	0.92	4.05	10.31	1.35	0.00	0.00	0.00	0.00	0.00	16.84
7~8	0.00	0.05	0.05	0.11	0.77	7.62	2.82	0.00	0.00	0.00	0.00	11.43
8~9	0.00	0.00	0.03	0.01	0.01	0.05	1.88	1.17	0.02	0.00	0.00	3.18
9~10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.07	0.19	0.01	0.00	0.29
>=10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.02
Total	15.24	27.64	18.50	12.24	11.17	9.02	4.70	1.24	0.21	0.02	0.01	100.00

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