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Influence of pile-soil-interaction on natural frequency of bottom-fixed offshore wind turbines considering material uncertainties

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ABSTRACT

Monopiles have been most widely utilized for supporting offshore wind turbines (OWTs) in shallow waters. However, multi-member lattice-type structures including jackets and tripods are being also considered as one of the good alternatives to monopile foundations for relatively deep water in the range of 25-50 m of water depth owing to their technical and economic feasibility. Moreover, jacket structures are conventionally used in the oil and gas industry very popularly. However, there are still several issues need to be solved for utilization of multi-member lattice-type supporting structures for OWTs including pile-soil-interaction (PSI) effects, dynamically stable design, installation, and so on. In this study, the PSI effects on the dynamic properties of bottom-fixed OWTs are intensively investigated including monopile-, tripod- and jacket-supported OWTs. The tower and substructure are modeled using conventional beam elements with added mass and the pile foundations are modeled with beam and nonlinear spring elements, and the PSI effects on dynamic properties of the structure are evaluated using Monte Carlo simulation considering uncertainties in soil properties.

1. INTRODUCTION

Monopile foundations have been most widely utilized for supporting OWTs in shallow waters usually less than 30 m. However, multi-member lattice-type

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substructures like jackets and tripods are being considered as one of the good alternatives to the monopile foundations for relatively deep water in the range of 25–50 m of water depth as shown in Fig. 1 (EWEA 2013). Jacket structures are already one of the most widely used conventional types for offshore platforms in the oil and gas industry. However, there are still several issues unsolved for utilization of multi-member lattice-type substructures for OWTs including PSI analysis, dynamically stable design, economic fabrication, installation, and so on. In this study, the PSI effects on the dynamic properties of OWTs with bottom-fixed supporting structures are intensively investigated considering material uncertainties in soil properties.

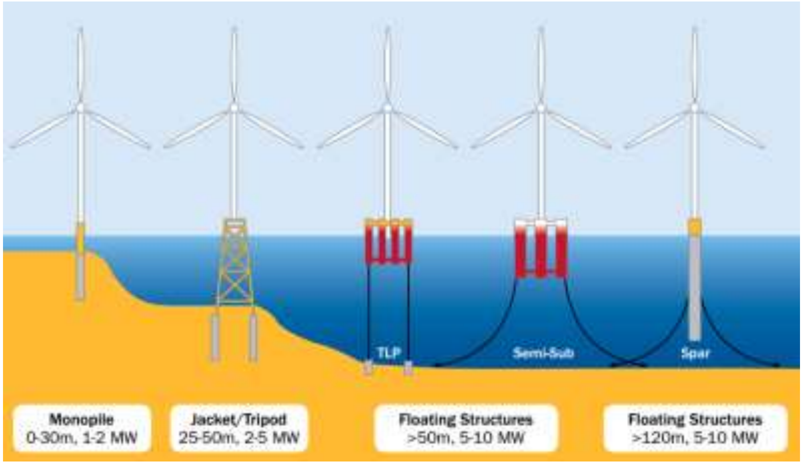


Fig. 1. Offshore wind foundations (EWEA, 2013)

The multi-member lattice-type substructures can be designed as three or four-legged structures, and the external loads can be transmitted to the ground via gravity based footing, suction anchors, or pile foundations. Among them pile foundations are more widely applied in diverse soil conditions while gravity based footings and suction foundations can be applied in specific soil conditions. Piles can be installed as inner piles (or post piles) and pin piles (or pre piles). In the case of offshore wind farms, pin piles pre-installed using a template can be good alternatives from installation and economic points of view. In this study, the typical bottom-fixed OWTs with monopiles and vertical pre-piles (for tripod- and jacket-type structures) are utilized as example structures. The PSI effects on the dynamic properties are evaluated using Monte Carlo simulation considering the uncertainties in the soil properties. As well known, there are three design concepts for supporting structures regarding dynamic interaction: soft–soft, soft–stiff and stiff–stiff considering the resonance frequency relative to the rotor rotational frequency (1P) and blade-passing frequency (3P), see Fig. 2. Usually soft–stiff design concepts are accepted for bottom-fixed OWTs supported by monopiles or jackets. If the natural frequencies of the structure fall within the frequency ranges related to rotor imbalances (1P) or blade passing (3P), redesign is required to avoid resonance and high possibility of fatigue failure. For this purpose, more reliable dynamic analysis is necessary with consideration of the PSI effect including the uncertainties of soil layers.

The PSI analysis can be conducted using several approaches including the apparent fixity method, coupled model, and Winkler's spring model. The Winkler spring model with p–y, t–z and q–z soil springs is utilized in this study. For the dynamic analysis of OWTs using a Winkler spring model, several researches have been carried out (Alexander and Bhattacharya, 2011; Bisoi and Haldar, 2014; Carswell 2012; Carswell et al, 2014, Martinez-Chaluisant, 2011; Pradhan, 2012; Song et al. 2014; Van Buren and Muskulusa, 2012). However, there are still several unsolved issues regarding dynamic modelling of PSI as described in the next section.

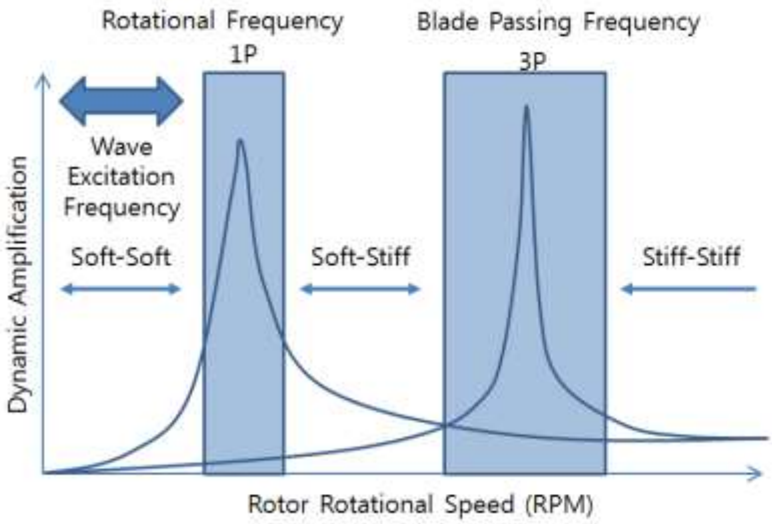


Fig. 2 Basic design concept of wind turbines for avoiding dynamic instability due to resonance

2. PILE-SOIL-INTERACTION MODELS

Pile foundations are an essential structural type of bottom-fixed OWTs including jacket-type foundations and the PSI is of major concern regarding the structural behavior in the nonlinear range of deformation. The PSI system can be modeled as part of the pile-soil-structure interaction analysis which considers nonlinear properties of the underlying soil. Usually piles are modeled down to the actual penetration depth, and the soil stiffness is simulated by nonlinear soil springs attached to nodal points in a pile along its buried depth.

In this paper, a pile is modeled by beam elements with a Young's modulus of 210 GPa and a mass density of 7850 kg/m^3. The surrounding soils are discretized by nonlinear soil springs to consider PSI effects. The t–z and q–z curves are based on API (2005), and p–y curves are based on API (2005) and Evans and Duncan (1992) for clay and sand layers, respectively.

As well known, the PSI is inherently nonlinear; hence, a reasonable linearization is necessary for the linear modal analysis to calculate natural frequencies to check the dynamic instability considering the range of rotor rotational and blade-passing frequencies in OWT’s operation. However, no commonly acceptable approach exists for linearization of the nonlinear soil spring models so far. If the loading time history data are given, nonlinear dynamic analysis can be carried out. However, loading and unloading curves for the soil response must be available even in these cases.

In this study, the nonlinear soil springs are linearized considering the equivalent load amplitude which is obtained mainly from the thrust force time history data by a coupled analysis program such as FAST or HAWC2 (see Fig. 3). The thrust forces, which are main external loads in OWTs, are determined at the rated wind speed where high thrust forces with significant fluctuations are generated. Existing OWTs are designed with rated rotor speeds of, for example, 7-14 rounds per minute (RPM) leading to blade-passing speeds of 21-42 RPM. For new generations of OWTs, the cut-in rotational speed is reduced to extract more wind energy. Hence, the gap between the maximum allowable 1P frequency and the minimum allowable 3P frequency is closing. Because of this, soft–stiff design becomes more difficult and may require an enhanced modern control strategy such as variable speed control with the speed exclusive zone algorithm (Licari 2013).

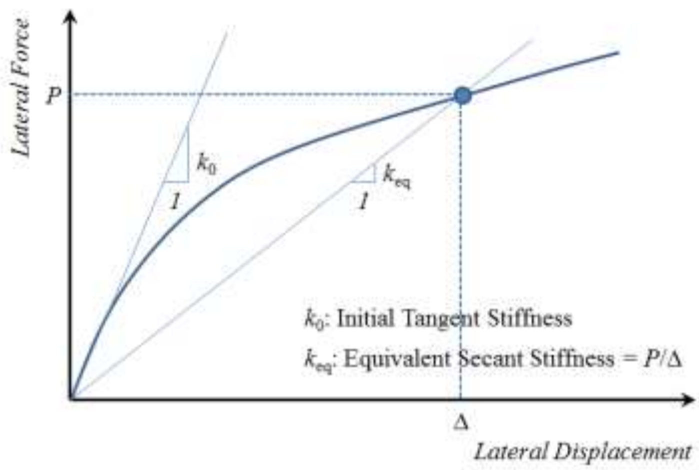
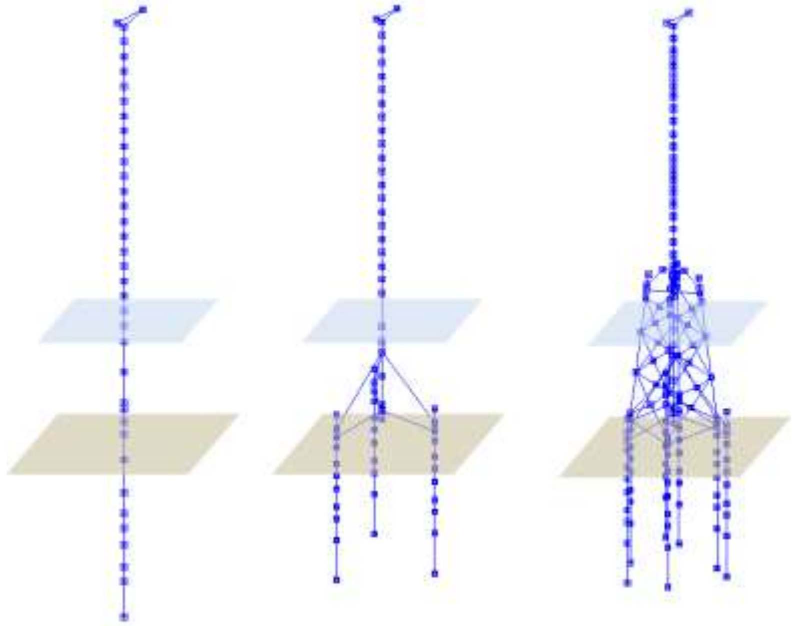


Fig. 3 Equivalent secant stiffness of nonlinear soil spring

3. EXAMPLE STUDY

3.1 Example Wind Turbine Model

The NREL 5 MW wind turbines, placed on a monopile, tripod and jacket substructure, are utilized in this study. The soil properties including statistical data are obtained from cone penetration tests (CPTs) carried out in the south-west coastal region of Korea. The pre-pile method is considered with vertical piles (not battered ones) for the cases of tripod- and jacket-type substructures as shown in Fig. 4. Details of the model are listed in Table 1. The rotor, hub and nacelle are simplified as a lumped mass at the top of the tower, i.e. rotor and hub masses are lumped at the mass center of hub and nacelle mass is placed at the mass center of nacelle.



(a) Monopile (b) Tripod (c) Jacket
Fig. 4 Wind turbine model with jacket (not scaled)

Table 1. Specification of OWT models
(a) Tower

Hub height	90 m
TP height	20 m
Tower thickness(top/bottom)	20 mm
Tower diameter(top/bottom)	3.87 m/ 6 m
Top mass (blades+hub+nacelle)	251.2 ton
Density	7,850 kg/m^3

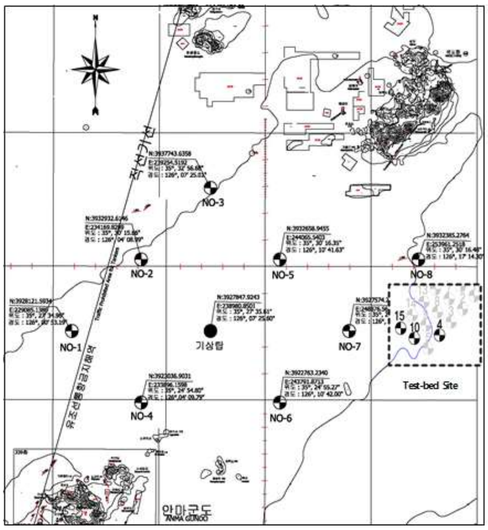
(b) Substructures

	Monopile	Tripod	Jacket
TP height	15.4 m	16.0 m	25.5 m
Pile diameter	5.7 m	2.5 m	1.45 m
Pile thickness	70 mm	40 mm	40 mm
Penetration Depth	30 m	40 m	40 m

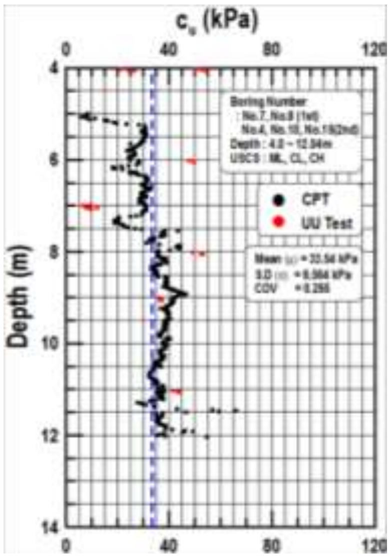
3.2 Uncertainties in Soil Properties

The first large-scale offshore wind farm project was initiated to develop the core technologies including planning, design, manufacturing, installation and O&M (operation and management) for offshore wind farms in Korea. The target site was situated in the south-west coastal region, and several soil investigation works such as

SPT and CPT were carried out to obtain the soil condition. Typical CPT data are shown in Fig. 5 and the statistical properties of each soil layer are summarized in Table 2. The values are mean values obtained from CPT and the coefficients of variation (COVs) are found to be 0.1 for the unit weight, 0.225 for the cohesion, and 0.062 for the internal angle of friction.



(a) Target site for offshore wind farm



(b) CPT data for BH-7

Fig. 5. Target site and CPT data for offshore wind farm in Korea

Table 2. Characteristic values for soil layers at the target site

Soil layers		Depth (m)	Unit weight		Cohesion		Angle of internal friction	
			Mean (kN/m^3)	COV	Mean (kPa)	COV	Mean (°)	COV
Silt	CH	0–5.0	17.0	0.1	20.00	0.225	-	0.062
	CL	5.0–12.3	18.0		33.54		-	
Sand	SM	12.3–23.0	19.0		16.63		31.59	
Silt	CL	23.0–30.0	18.0		60.00		-	

3.3 Numerical Analysis Results

Figure 6 shows one of the thrust force time histories obtained from FAST with the near-rated wind speed of 12.0 m/s without PSI effects for different normal turbulence models (NTM), i.e. NTM-A, B, and C. For a given wind speed, the statistical properties of the thrust forces (including the mean and standard deviation) are assumed to be the same whether the substructure is fixed at mud-line or the PSI model is introduced. As mentioned before, the equivalent load amplitude is decided using the standard deviation of the thrust force, and the nonlinear soil springs are linearized under the equivalent load amplitude at the top of the tower (i.e. at hub height). For simplicity, wave loading is not considered. It can easily be included in the analysis, but it will not be significant for this study.

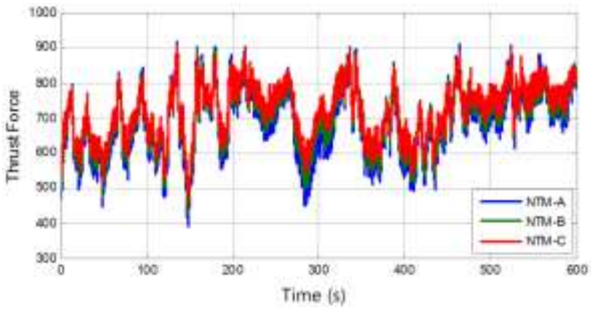


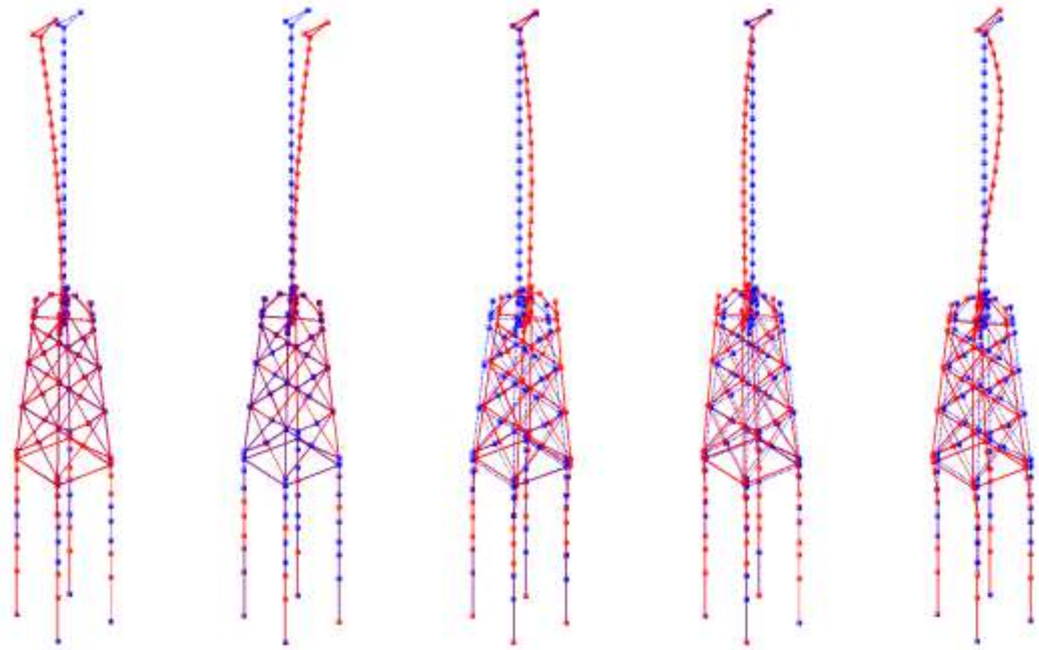
Fig. 6. Thrust force time history data under rated wind speed

Fig. 7 shows the mode shapes and natural frequencies calculated with the linearized soil springs obtained at the rated wind speed. The effect of the equivalent load amplitude can be included in the linearized soil spring stiffness; i.e. the secant stiffness will become smaller as the equivalent load amplitude becomes larger, and vice versa. To investigate the effect of equivalent load amplitude, the first natural frequency is compared with respect to the equivalent load amplitude of thrust force in Figs. 8 and 9. As expected, the natural frequency tends to become smaller as the equivalent load amplitude of the thrust force increases. For each loading conditions, one thousand samples are randomly generated considering the mean values and COVs of the soil properties. The histogram for the representative four cases are shown in Fig. 8 and the mean values plus/minus three standard deviation for all cases are shown in Fig. 9.

The mean value is gradually reduced from 0.2512 Hz to 0.2493 Hz, 0.2479 Hz, and so on for the case of monopile-supported OWT while that is from 0.2690 Hz to 0.2687 Hz, 0.2685 Hz, … and from 0.3240 Hz to 0.3230 Hz, 0.3223 Hz, … for tripod- and jacket-supported OWTs, respectively. When the equivalent load amplitude is increased from 10 kN to 210 kN, the mean value of the natural frequency is decreased as mentioned before and the reduction ratios for three different supporting structures are 4.86 %, 0.59 % and 1.82 % for monopile, tripod and jacket supported OWTs, respectively, as indicated in Table OO. The effect of equivalent load amplitude is more significant for the monopile-supported OWTs while it is less significant for the tripod case, which means that the nonlinear behavior of soil media affects more significantly for monopile case. Even though it is certainly true that the natural frequency is reduced as the equivalent load amplitude is increased, the change is small and almost negligible from a practical point of view at least for the cases of multi-member lattice-type substructures like tripods and jackets.

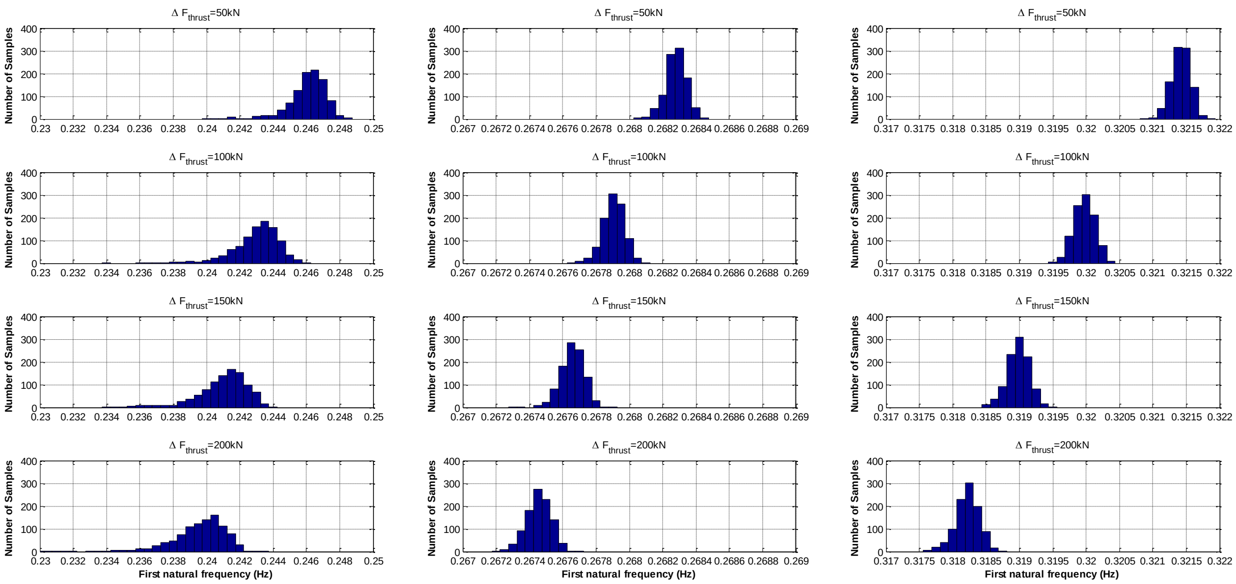
The first natural frequencies which are calculated considering the PSI effects are also compared with those without PSI effects, i.e. fixed and hinged cases in Table 3. It can be found that the natural frequency is reduced as amount of 12.3 % for the case of monopole-supported OWT while they are less than 1.4 % and 2.7 % for the cases of tripod and jacket substructures, respectively, by introducing nonlinear PSI effects. This means that the first natural frequency can be reasonably estimated by neglecting the

PSI effect in the cases of multi-member lattice-type substructures when the soil properties are not fully known or completely unknown in the preliminary design stage.



$f_1 = 0.3382Hz$ $\quad f_2 = 0.3393Hz$ $\quad f_3 = 2.4639Hz$ $\quad f_4 = 2.7159Hz$ $\quad f_5 = 4.8703Hz$

Fig. 7 Lower 5 modes for the 5 MW example wind turbine model



(a) Monopile-type OWTs (b) Tripod-type OWTs (c) Jacket-type OWTs

Fig. 8 Histogram of first natural frequencies from 1000 samples

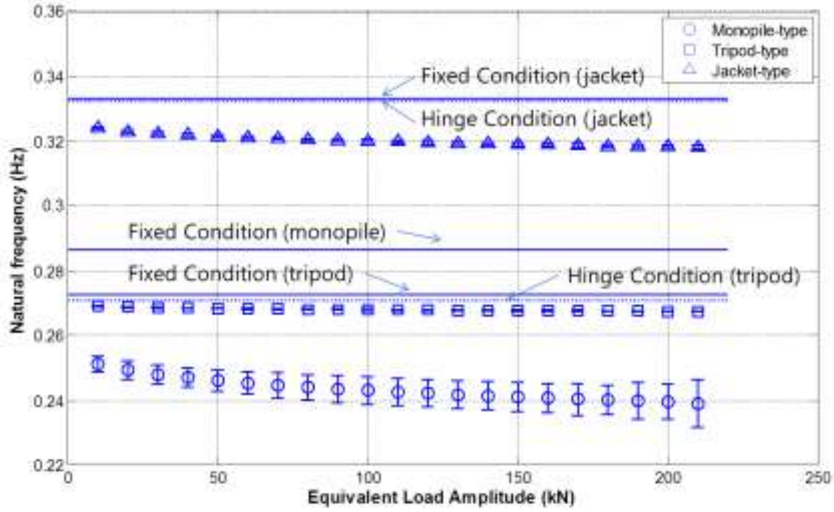


Fig. 9 μ and $\mu \pm 3\sigma$ of first natural frequencies with different equivalent load amplitudes

Table 3. Natural frequencies for various conditions

Case		Monopile	Tripod	Jacket
Fixed	f_1^{fixed} (Hz)	0.2864	0.2728	0.3329
Hinged	f_1^{hinged} (Hz)	-	0.271	0.3322
	1- f_1^{hinged} / f_1^{fixed} (%)	-	0.66%	0.21%
P=10kN	$f_1^{P=10kN}$ (Hz)	0.2512	0.2690	0.3240
	1- $f_1^{P=10kN}$ / f_1^{fixed} (%)	12.29%	1.39%	2.67%
P=210kN	$f_1^{P=210kN}$ (Hz)	0.2390	0.2674	0.3181
	1- $f_1^{P=210kN}$ / $f_1^{P=10kN}$ (%)	4.86%	0.59%	1.82%

4. CONCLUDING REMARKS

From the numerical analysis of the NREL 5 MW wind turbine models supported by monopole, tripod and jacket substructures, the PSI effects on the natural frequencies are investigated and it is found that the uncertainties of soil properties can affect the first natural frequency distributions under several conditions with different equivalent loading amplitudes. The stiffness of soil springs decreases as the equivalent loading amplitude increases, which implies a reduction of the natural frequency. However, the reduction is small (less than 2%) and may thus be negligible from a practical point of view for the cases of tripod- and jacket-supported OWTs.

One interesting observation is that the natural frequency is getting more significantly affected by the equivalent load amplitude in the case of the monopile-type OWT. And also it is observed that the variability of natural frequency is larger in the cases of the monopile-type OWT. It means that the PSI effects on the natural frequency of tripod- and jacket-supported OWTs are less significant than that of a monopile-type OWT. In other words, the jacket-supported OWT is more robust regarding consistency of the natural frequency under different equivalent load amplitudes and uncertain soil conditions. Of course, the optimal water depths for monopile and jacket foundations are quite different; i.e. in shallow water less than 30 m deep, the monopile foundation can be more efficiently utilized, while in intermediate water depths of 25–50 m, the jacket foundation is attractive. However, in water depths between 20 and 30 m, the jacket and monopile foundations are still competitive with each other and both of them can be applicable depending on site conditions such as soil conditions. Economic feasibility to reduce the cost of energy will be the first index for deciding which foundation type to use within this range.

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