Wind and Structures, *Vol. 21, No. 6 (2015) 625-639*
DOI: http://dx.doi.org/10.12989/was.2015.21.6.625

Natural frequency of bottom-fixed offshore wind turbines considering pile-soil-interaction with material uncertainties and scouring depth

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(Received November 15, 2015, Revised December 3, 2015, Accepted December 7, 2015)

Abstract. Monopiles have been most widely used for supporting offshore wind turbines (OWTs) in shallow water areas. However, multi-member lattice-type structures such as jackets and tripods are also considered good alternatives to monopile foundations for relatively deep water areas with depth ranging from 25–50 m owing to their technical and economic feasibility. Moreover, jacket structures have been popular in the oil and gas industry for a long time. However, several unsolved technical issues still persist in the utilization of multi-member lattice-type supporting structures for OWTs; these problems include pile-soil-interaction (PSI) effects, realization of dynamically stable designs to avoid resonances, and quick and safe installation in remote areas. In this study, the effects of PSI on the dynamic properties of bottom-fixed OWTs, including monopile-, tripod- and jacket-supported OWTs, were investigated intensively. The tower and substructure were modeled using conventional beam elements with added mass, and pile foundations were modeled with beam and nonlinear spring elements. The effects of PSI on the dynamic properties of the structure were evaluated using Monte Carlo simulation considering the load amplitude, scouring depth, and the uncertainties in soil properties.

Keywords: pile-soil-interaction (PSI); bottom-fixed offshore wind turbine; random sampling; natural frequency; scouring

1. Introduction

Monopile foundations have been most widely used for supporting offshore wind turbines (OWTs) in shallow water area usually less than 30 m deep and many relevant studies have been carried (Adhikari and Bhattacharya 2011, Alati *et al*. 2014, Kim *et al*. 2014). However, multi-member lattice-type substructures such as jackets and tripods are being considered as good

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http://www.techno-press.org/?journal=was&subpage=8 ISSN: 1226-6116 (Print), 1598-6225 (Online)

alternatives to monopile foundations for relatively deep water areas having depth in the range 25–50 m (Fig. 1; EWEA 2013). Jacket substructures are already one of the most widely used conventional supports for offshore platforms in the oil and gas industry. However, there are still several unsolved technical problems in the use of multi-member lattice-type substructures for OWTs; these include performing pile-soil-interaction (PSI) analysis, realizing a dynamically stable design to avoid resonances, economic fabrication, and quick and safe installation in remote areas. In this study, the effects of PSI on the dynamic properties of OWTs with bottom-fixed supporting structures are intensively investigated by considering the load amplitude, scouring depth and the material uncertainties in soil properties.

Multi-member lattice-type substructures can be designed as three or four-legged structures and external loads can be transmitted to the ground through gravity-based footing, suction anchors, or pile foundations. Pile foundations are most widely used under diverse soil conditions, while gravity-based footings and suction foundations are used under specific soil conditions. Gravity-based footings are used under relatively good soil conditions, such as rocky conditions, while suction bucket foundations are a better alternative under sandy or silty soil conditions. Piles can be installed in the form of 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, are a good alternative from the perspectives of installation and economy. In this study, typical bottom-fixed OWTs with monopiles and vertical pre-piles (for tripod- and jacket-type structures) were considered as example structures. The effects of PSI on dynamic properties were evaluated through a Monte Carlo simulation considering the uncertainties in the soil properties.

As well known, there are three design concepts for supporting structures from the viewpoint of dynamic interaction with external forces driven by rotating blades: soft–soft, soft–stiff, and stiff–stiff, considering the resonance frequency relative to the rotor rotational frequency (1P) and blade-passing frequency (3P) (Fig. 2). Usually the 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), redesigning is necessary to avoid resonance and high possibility of fatigue failure. For this purpose, more reliable dynamic analysis considering the PSI effects, including the uncertainties in soil layers, load amplitude, and scouring depth, is necessary.

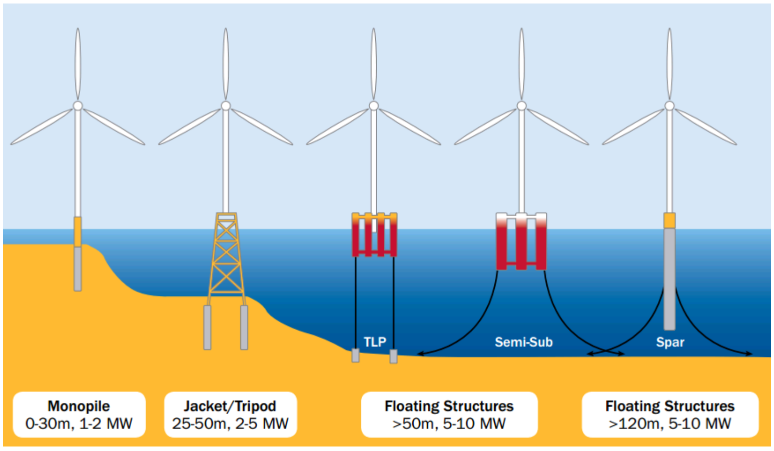


Fig. 1 Offshore wind foundations (EWEA, 2013)

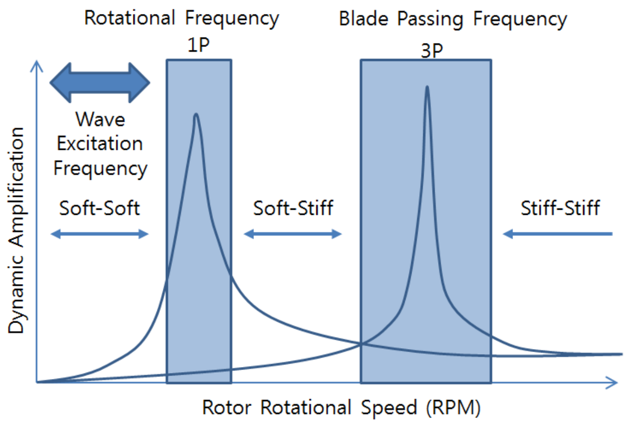


Fig. 2 Basic design concept of wind turbines for avoiding dynamic instability due to resonance

The PSI analysis can be conducted using several approaches such as 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 adopted in this study. Several studies have been carried out on the dynamic analysis of OWTs by using a Winkler's spring model (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, several unsolved problems persist in the dynamic modeling of PSI, as described in the next section.

2. Pile-soil-Interaction models

Pile foundations are an essential structure in bottom-fixed OWTs, including those with jacket-type foundations. PSI is a major concern from the perspective of 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 the 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 study, 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 soil is discretized by nonlinear soil springs to consider PSI effects. Typical PSI spring models are shown in Fig. 3. The *t–z* and *q–z* curves are based on API (2005), and the *p–y* curves are based on API (2005) for clay and Evans and Duncan (1992) for sand layers as follows

<u>*p-y* curve</u>

$$\frac{p}{p_u} = \frac{1}{2}\left(\frac{y}{y_{50}}\right)^{1/3} \quad \text{where} \quad y_{50} = 2.5 \cdot \varepsilon_{50} \cdot D \tag{1}$$

sand : $p_u = \min(p_{us}, p_{ud})$

$$\frac{p}{p_u} = A \cdot \tanh \frac{y}{y_c} \quad \text{where} \quad y_c = \frac{A}{k_1} \frac{p_u}{z}$$

clay : $p_u = s \cdot c_u \cdot D + \sigma_z{}' \cdot D + J \cdot c_u \cdot z$

$p_u = 9 \cdot c_u \cdot D \ \ (z \geq X_R)$

where, p : Lateral resistance at deflection y

p_u : Ultimate lateral resistance

y : Deflection at depth z

D : Pile diameter

ε_{50} : Strain at one-half the maximum stress of undrained compression tests

$\sigma_z{}'$: Effective overburden pressure at depth z

<u>*t*-z curve</u>

$$\frac{f}{f_{max}} = \frac{w}{w_{max}} \quad (w \leq w_{\max}) \tag{2}$$

$f = f_{max} \quad (w > w_{max})$ where $w_{max} = 2.54mm$

sand : $f_{max} = K \ \tan\delta \ \sigma_z{}' \leq f_{limit}$

clay : $f_{max} = \alpha \ c_u$

$\alpha = 0.5\psi^{-0.5} \leq 1, \ \psi \leq 1$

$\alpha = 0.5\psi^{-0.25} \leq 1, \ \psi > 1$

$\psi = c_u / \sigma_z{}'$

where, f : Skin friction at vertical displacement w

w : Vertical displacement at depth z

f_{max} : Maximum skin friction

K : Coefficient of lateral earth pressure

δ : Friction angle between the soil and pile wall

f_{limit} : Limiting skin friction

c_u : Undrained shear strength at depth z

<u>*q*-z curve</u>

$$\frac{q}{q_{max}} = \frac{z_b}{z_{max}}^{1/3} \quad (z_b \leq z_{max}) \tag{3}$$

$q \leq q_{max} \quad (z_b > z_{max})$

sand : $q_{max} = N_q \ \sigma_z{}' \leq q_{limit}$

clay : $q_{max} = 9 \cdot c_u$

where, q_{max} : Maximum tip resistance

N_q : Bearing capacity factor, function of internal friction angle (ϕ)

$\sigma_z{}'$: Effective overburden pressure at pile tip

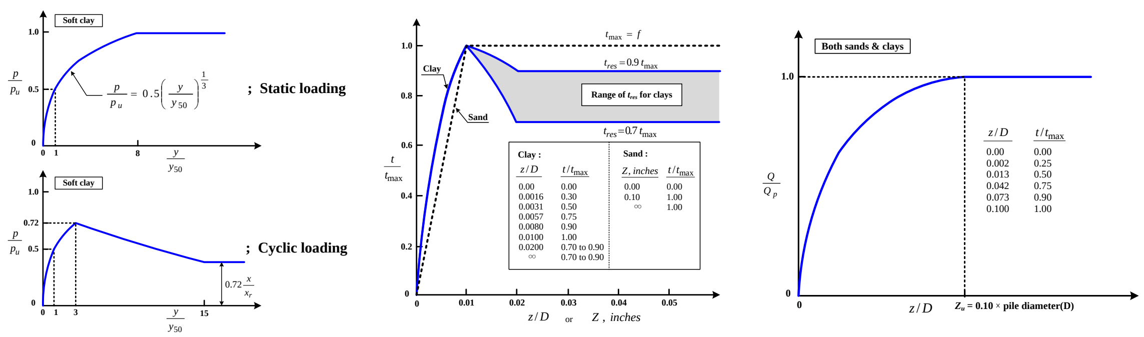
q_{limit} : Limiting unit end bearing value

z_b : Tip displacement

z_{max} : Tip displacement at $q = q_{max}$

As shown in Fig. 3, the PSI is inherently nonlinear; hence, a reasonable linearization is necessary for performing the linear modal analysis to calculate the natural frequencies to check the dynamic instability considering the range of rotor rotational and blade-passing frequencies in the operation of the OWT. However, no commonly acceptable approach exists for linearizing 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 soil response must be available even in these cases.

In this study, the nonlinear soil springs were linearized considering the equivalent load amplitude that can be obtained mainly from the thrust force time history data by using a coupled analysis program such as FAST (Jonkman and Buhl Jr. 2005) or HAWC2 (Larsen and Hansen 2007, Fig. 4). The thrust forces, which are the main external loads in OWTs, were determined for the rated wind speed where high thrust forces with significant fluctuations were generated. The existing three-bladed OWTs were designed at the rated rotor speeds of 7–14 rounds per minute (RPM), for example, leading to blade-passing speeds of 21–42 RPM. For new generation OWTs, the cut-in rotational speed was reduced to extract more wind energy. Hence, the gap between the maximum allowable 1P frequency and the minimum allowable 3P frequency is decreasing. Hence, it becomes more difficult to incorporate the soft–stiff design, and an enhanced modern control strategy such as variable speed control with the speed exclusive zone algorithm may be necessary (Licari 2013). It is also noticed that the natural frequency refers the undamped natural frequency hence the soil damping generated by hysteresis is not affected in the natural frequency. However it is beneficial to additionally investigate the damping effects related to the response of a whole system with aerodynamic damping effects for better understanding on the dynamics of a wind turbine system.



(a) *p-y* curve (b) *t-z* curve (c) *q-z* curve

Fig. 3 Typical pile-soil spring models

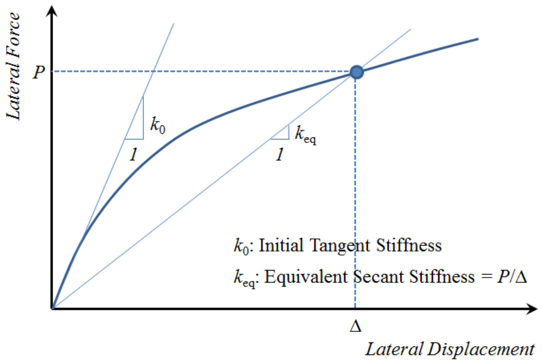


Fig. 4 Equivalent secant stiffness of the nonlinear soil spring

3. Example model and soil condition

3.1 An Example of a wind turbine model

The NREL 5 MW wind turbines, supported by a monopile, tripod, and jacket substructure, were considered in this study. The soil properties, including statistical data, were obtained through cone penetration tests (CPTs) carried out in the south-west coastal region of Korea (KEPRI, 2013). The pre-pile method was considered with vertical piles (not battered ones) for the tripod and jacket substructures, as shown in Fig. 5. Details of the model are listed in Table 1. The rotor, hub, and nacelle were simplified and considered as a lumped mass at the top of the tower, i.e., the rotor and hub masses were lumped at the mass center of the hub, and the nacelle mass was placed at the mass center of the nacelle.

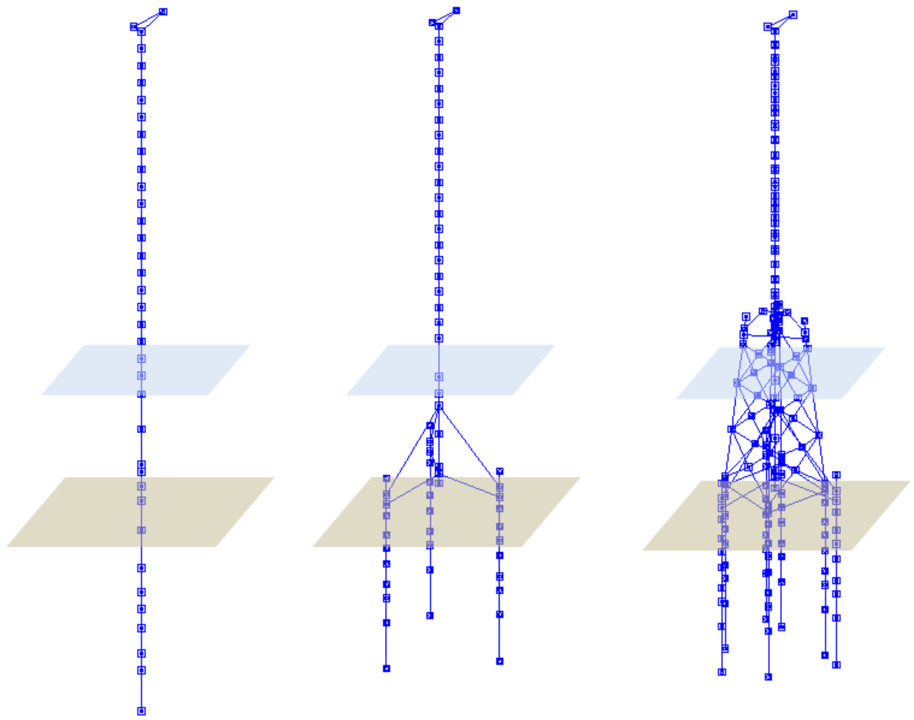
Table 1 Specification of OWT models

(a)

Hub height	90 m
Height of transition piece	20 m
Tower thickness (top/bottom)	20 mm / 50 mm
Tower diameter (top/bottom)	3.87 m/ 6 m
Top mass (blades + hub + nacelle)	251.2 ton
Density	7,850 kg/m^3

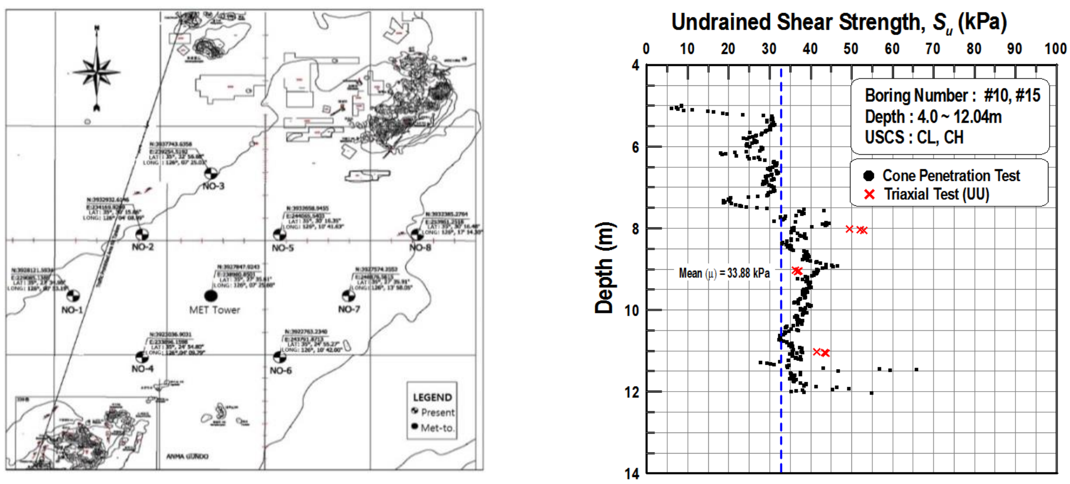
(b)

	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



(a) Monopile substructure (b) Tripod substructure (c) Jacket substructure

Fig. 5 Wind turbine models with different substructures (not scaled)



(a) The target site for the offshore wind farm (b) CPT data for BH-7

Fig. 6 The target site and CPT data for the 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
Clay	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	
Clay	CL	23.0–30.0	18.0		60.00		-	

3.2 Uncertainties in soil properties

The first large-scale offshore wind farm project was initiated to develop the core technologies such as planning, design, manufacturing, installation, and operation and management for offshore wind farms in Korea (KEPRI, 2013). The target site was situated in the south-west coastal region, and several soil investigation works such as standard penetration test (SPT) and CPT were carried out to determine the soil condition. The typical CPT data are shown in Fig. 6, 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) were found to be 0.1 for unit weight, 0.225 for cohesion, and 0.062 for the angle of internal friction.

4. Results and discussion

4.1 Numerical analysis results considering material uncertainties

Fig. 7 shows one of the thrust force time histories obtained from FAST with a near-rated wind speed of 12.0 m/s without PSI effects for the normal turbulence models (NTM) NTM-A, B, and C. For a given wind speed, the statistical properties of the thrust forces (including the mean and standard deviation) were assumed to be the same regardless of the substructure being fixed at mud-line or the PSI model being used. As mentioned before, the equivalent load amplitude was set based on the standard deviation of the thrust force, and the nonlinear soil springs were linearized under the equivalent load amplitude at the top of the tower (i.e., at hub height). For simplicity, wave loading was not considered because although it could be easily included in the analysis, it would not be significant for this study.

Fig. 8 shows the mode shapes and natural frequencies calculated considering the linearized soil springs at the rated wind speed for the case of the jacket-supported OWT model. The effect of the equivalent load amplitude can be included in the linearized stiffness of a soil spring; that is, the secant stiffness decreases as the equivalent load amplitude increases, and vice versa. To investigate the effect of equivalent load amplitude, the first natural frequency was compared with respect to the equivalent load amplitude of the thrust force (Figs. 9 and 10). As expected, the natural frequency tends to decrease as the equivalent load amplitude of the thrust force increases. For each loading condition, 1000 samples were randomly generated considering the mean values and COVs of the soil properties. The histogram for the four representative cases are shown in Fig. 9, and the mean values and the mean values plus and minus three standard deviations for all cases are shown in Fig. 10.

The mean value was gradually reduced from 0.2512 Hz to 0.2493 Hz, 0.2479 Hz, and kept on decreasing for the monopile-supported OWT, while that for the tripod-supported OWT was reduced from 0.2690 Hz to 0.2687 Hz, 0.2685 Hz, …, and that for the jacket-supported OWT was reduced from 0.3256 Hz to 0.3230 Hz, 0.3223 Hz, … When the equivalent load amplitude was increased from 10 kN to 210 kN, the mean value of the first natural frequency decreased as mentioned before, and the reduction ratios were 4.86%, 0.59%, and 1.32% for the monopile-, tripod-, and jacket-supported OWTs, respectively (Table 3).

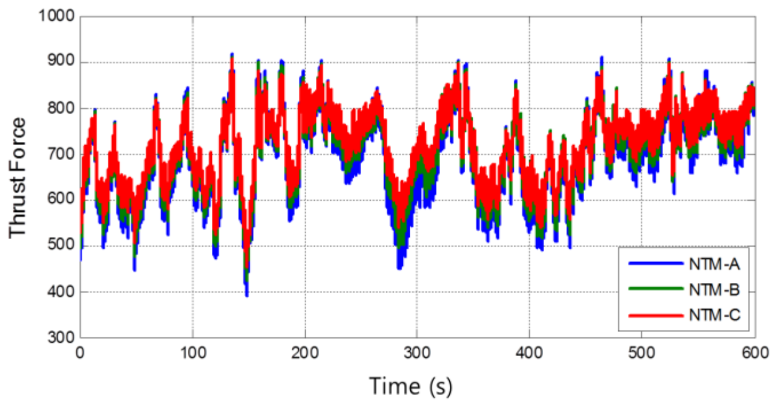
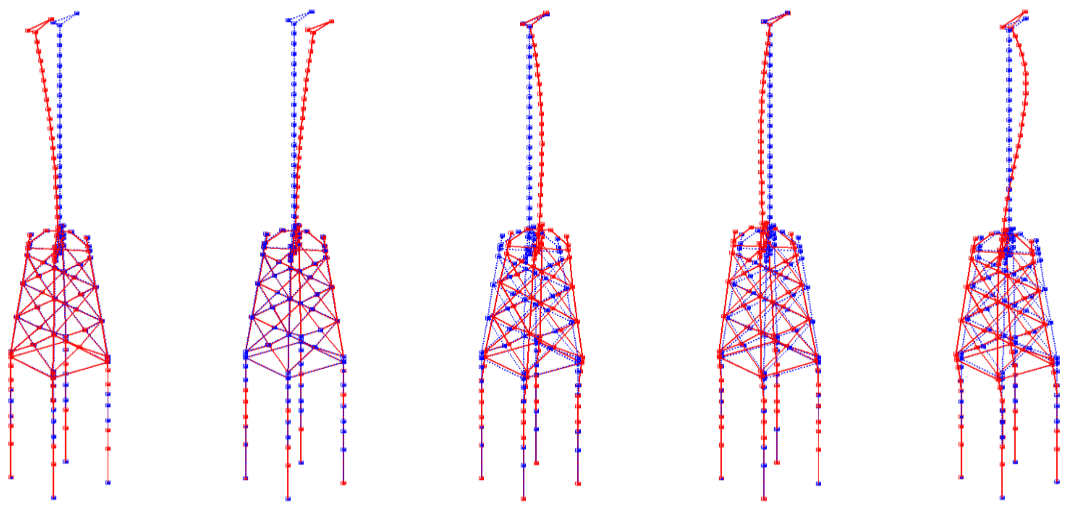


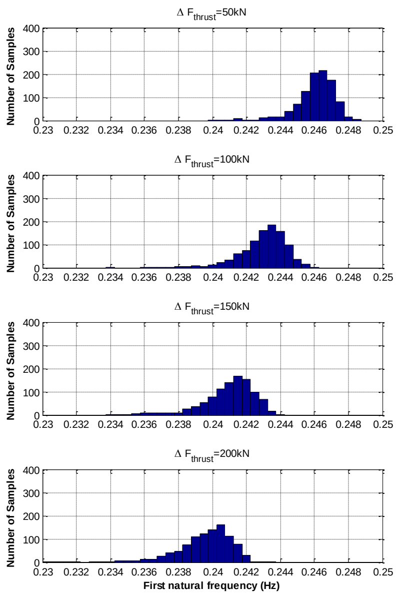
Fig. 7 Thrust force time history data under rated wind speed



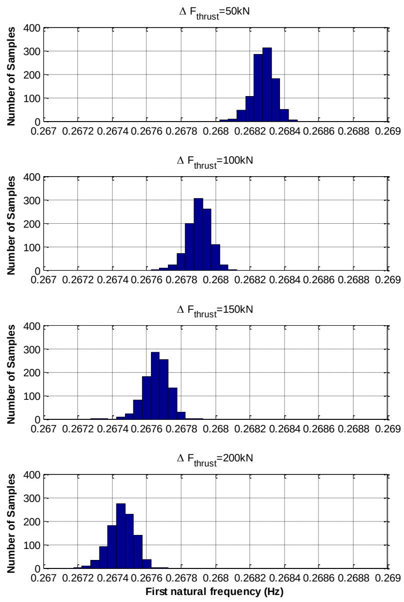
$f_1 = 0.3382\,\mathrm{Hz}$ $f_2 = 0.3393\,\mathrm{Hz}$ $f_3 = 2.4639\,\mathrm{Hz}$ $f_4 = 2.7159\,\mathrm{Hz}$ $f_5 = 4.8703\,\mathrm{Hz}$

Fig. 8 The first five modes for the 5 MW wind turbine model considered in the study (Jacket Type)

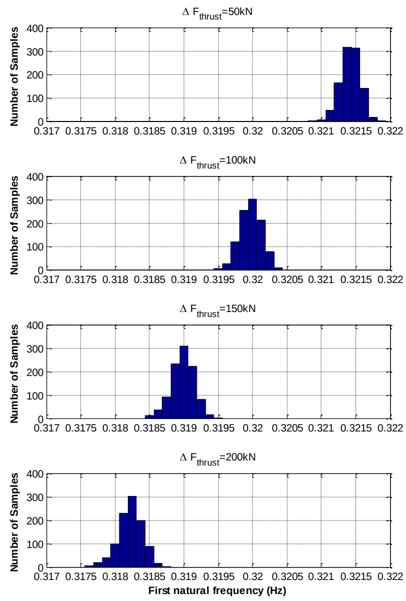
The effect of equivalent load amplitude is more significant in the case of the monopile-supported OWTs, while it was less significant in the case of the tripod; this indicates that the nonlinear behavior of soil media affects the monopile-supported OWTs to a greater extent. Although the natural frequency decreases as the equivalent load amplitude increases, the change is small, and it is almost negligible from a practical point of view at least for the case of multi-member lattice-type substructures such as tripods and jackets.



(a) Monopile-type OWTs



(b) Tripod-type OWTs



(c) Jacket-type OWTs

Fig. 9 Histograms of the first natural frequencies from 1000 samples

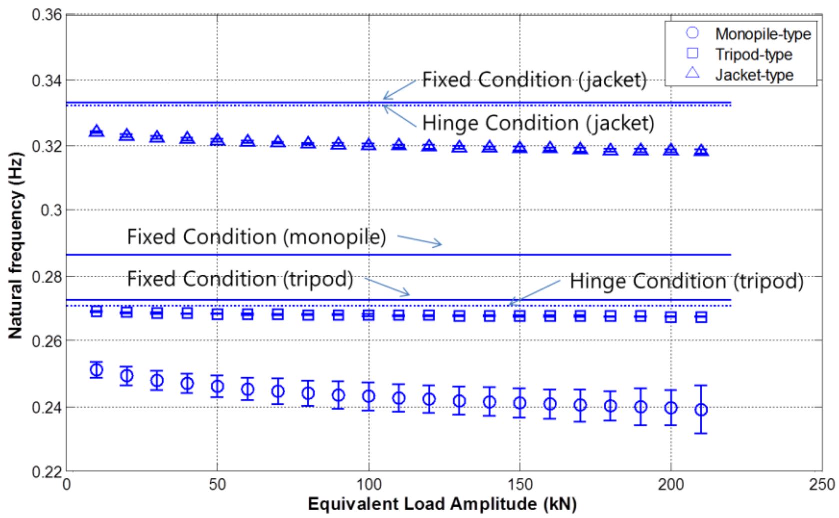


Fig. 10 The μ and $\mu \pm 3\sigma$ of the first natural frequencies with different equivalent load amplitudes

The first natural frequencies, which were calculated considering the PSI effects, were also compared with those without PSI effects, i.e., the fixed and hinged cases in Table 3. The first natural frequency decreased by 12.3% in the case of the monopile-supported OWT, while the reductions were less than 1.4% and 2.2% in the cases of tripod- and jacket-supported OWTs, respectively, when nonlinear PSI effects were introduced. This means that the first natural frequency can be reasonably estimated simply by neglecting the PSI effect in the case of multi-member lattice-type substructures when the soil properties are not fully known or are completely unknown in the preliminary design stage.

Table 3 Natural frequencies under various boundary and loading conditions

PSI models	Boundary conditions (BCs) and equivalent loading conditions		Type of substructures		
			Monopile	Tripod	Jacket
w/o PSI models	Fixed BCs	f_1^{fixed} (Hz)	0.2864	0.2728	0.3329
	Hinged BCs	f_1^{hinged} (Hz)	N/A	0.2710	0.3328
		1- f_1^{hinged} / f_1^{fixed} (%)	N/A	0.66	0.03
w/ PSI models	P = 10 kN	$f_1^{P=10kN}$ (Hz)	0.2512	0.2690	0.3256
		1- $f_1^{P=10kN}$ / f_1^{fixed} (%)	12.29	1.39	2.19
	P = 210 kN	$f_1^{P=210kN}$ (Hz)	0.2390	0.2674	0.3213
		1- $f_1^{P=210kN}$ / $f_1^{P=10kN}$ (%)	4.86	0.59	1.32

4.2 Numerical analysis results considering scouring depth

Scouring is one of major factors that can lead to the structural and geotechnical failure of coastal and offshore structures under sandy and clay soil conditions with high tidal current flow. Without appropriate scouring protection, the scouring depth may increase up to 1.5 times the pile diameter, and soil sedimentation can be stabilized afterward. In some cases, scouring and backfilling occur repeatedly near the pile structure, particularly, at locations where bi-directional tidal current flow exists. The coastal and offshore structures in the south and west coastal areas in Korea are susceptible to scouring because of the high-speed tidal current flow and soil characteristics with deep clay soil layers in the region. Several public reports on scouring depth and its impact on natural frequency near the offshore wind turbine supporting structures have been published (Van Der Tempel *et al*. 2004, Høgedal and Hald 2005, Damgaard *et al*. 2013). Very recently, Weinert (2015) reported that the scouring caused more significant effects on the natural frequency than other environmental effects including corrosion, water level change, and marine growth, and the natural frequency was reduced as amount of 5.04% when there was a scouring with a depth of 1.3 times of pile diameter in the case of monopile-type OWTs.

Excessive scouring can cause undesirable structural instability; hence, the scouring depth needs to be considered in advance in the design phases, and scouring protection should be adopted to prevent any undesirable scouring event. However, the scouring depth needs to be first considered in the design phase from the conservative design point of view. However, even in this case, the first natural frequency range needs to be checked. This means that the upper bound of the first natural frequency should be lower than the blade passing frequency, i.e., 3P; at the same time, the lower bound of the first natural frequency should be higher than the rotor rotational frequency, i.e., 1P (Fig. 2).

In this study, scouring was considered in the PSI analysis by using the same OWT models for the sensitivity analysis with respect to the scouring depth. The effect of scouring depth on natural frequency was investigated by increasing the scouring depth to 50%, 100%, 150%, and 200% with respect to the pile diameter as shown in Fig. 11. The results are summarized in Fig. 12. The first natural frequency changed by only a very little amount, and in the cases of the tripod- and jacket-supported OWTs, this change was negligible.

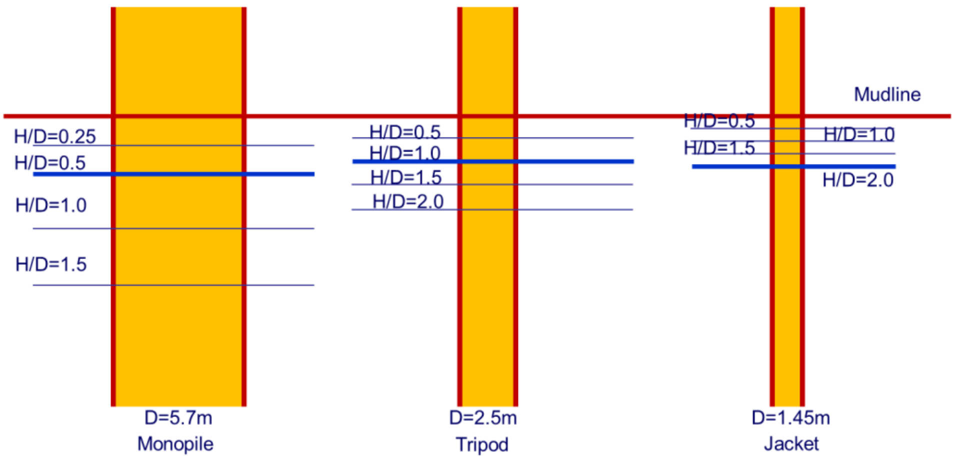


Fig. 11 Considered scouring depth with respect to substructure types

However, in the case of monopile-supported OWTs, there was a significant reduction in natural frequency, and the natural frequency significantly drops between 50% and 100% of scouring depth ratio. Therefore, it is very important to consider the scouring depth in the case of monopile-supported OWTs. When the first natural frequencies are compared for cases with similar absolute values around 2 m, it can also be found that the effect of scouring depth caused relatively larger changes in the case of monopile-supported OWTs.

Table 4 shows the natural frequencies under various conditions with and without scouring and it can be observed that the frequency change is under 0.2% in the cases of tripod- and jacket-supported OWTs due to the scouring with 50% of the pile diameter. However it can be increased up to 1.6 to 5.2% in the case of monopile-supported OWTs and also the frequency change is more significant as a level of external load is larger, which means the sensitivity of scouring on the natural frequency is also dependent to the level of external load due to the nonlinearity of soil springs.

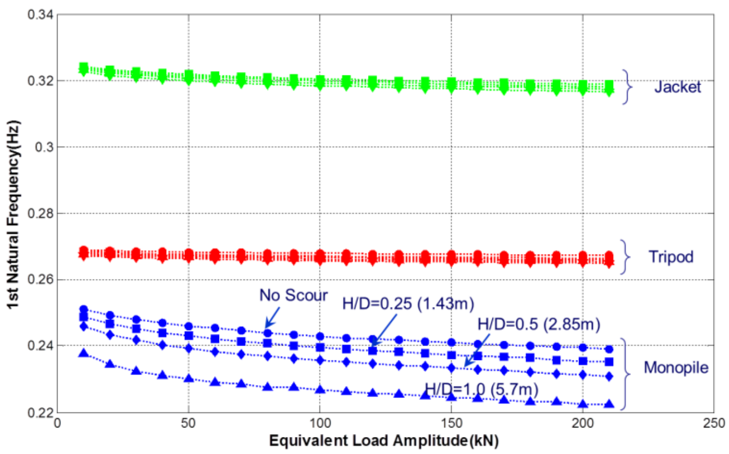


Fig. 12 Changes in the natural frequency with respect to changes in the scouring depth from 0% to 200%

Table 4 Natural frequencies under various conditions with and without scouring

Scouring conditions	Equivalent loading conditions		Type of substructures		
			Monopile	Tripod	Jacket
Without scouring	P = 10 kN	$f_1^{P=10kN\ w/o\ scouring}$ (Hz)	0.2512	0.2690	0.3256
	P = 210 kN	$f_1^{P=210kN\ w/o\ scouring}$ (Hz)	0.2390	0.2674	0.3213
With scouring (H/D=0.5)	P = 10 kN	$f_1^{P=10kN.H/D=0.5}$ (Hz)	0.2407	0.2687	0.3251
		1- $f_1^{P=10kN,H/D=0.5}$ / $f_1^{P=10kN\ w/o\ scouring}$ (%)	1.67	0.11	0.15
	P = 210 kN	$f_1^{P=210kN,H/D=0.5}$ (Hz)	0.2265	0.2671	0.3205
		1- $f_1^{P=210kN,H/D=0.5}$ / $f_1^{P=210kN\ w/o\ scouring}$ (%)	5.23	0.11	0.25

5. Conclusions

Based on the numerical analysis by using the NREL 5 MW wind turbine models supported by monopile, tripod, and jacket substructures, the PSI effects on the first natural frequencies were intensively investigated. The uncertainties of soil properties were found to affect the first natural frequency distributions under different conditions of equivalent load amplitude and scouring depth. The linearized stiffness of a soil spring decreased as the equivalent load amplitude increased, implying a reduction of the natural frequency. However, the amount of reduction was very small (less than 2%) and was negligible from a practical point of view in the cases of tripod- and jacket-supported OWTs.

One interesting observation was that the natural frequency was more significantly affected by the equivalent load amplitude in the case of the monopile-type OWTs. Further, the variability of the first natural frequency was larger in the case of the monopile-type OWT. This means that the effects of PSI on the natural frequency of tripod- and jacket-supported OWTs are less significant than those on the natural frequency of a monopile-type OWT. In other words, the jacket-supported OWT is more robust in terms of the 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; the monopile foundation is more suitable for shallow water areas less than 30 m deep, while the jacket foundation is more suitable for intermediate water depths of 25–50 m. However, for water depths between 20 and 30 m, both jacket and monopile foundations are suitable, and either can be applied depending on the site conditions such as soil conditions. Economic feasibility to reduce the cost of energy will be the first index for deciding which foundation should be used for the 20–30 m depths, and technical issues related to dynamic stability can be also investigated to determine the OWTs suitable for a more reliable design.

Acknowledgements

This work was supported by the Korea Institute of Energy Technology Evaluation and Planning (KETEP) grant (20123030020110) and the international network programme “Reliability-based design of offshore wind turbines with focus on load estimation and dynamic soil–structure interaction” supported by the Danish Agency for Science Technology and Innovation Framework Grant No. 1370-00125A. The authors would like to express their appreciation for the financial support. This study is an extended work of the authors’ previous ones (Yi *et al*. 2015a, b).

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