Proceedings of the XVII ECSMGE-2019
Geotechnical Engineering foundation of the future
ISBN 978-9935-9436-1-3

doi: 10.32075/17ECSMGE-2019-0187

XVII European Conference
ECSMGE 2019
Reykjavik
on Soil Mechanics
and Geotechnical Engineering

Offshore wind turbine natural frequency evaluation for monopile and monopod foundations by centrifuge test

Évaluation de la fréquence naturelle des éoliennes offshore pour les fondations monopieux et monopodes par tests de centrifugeuse

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ABSTRACT: Precise evaluation of the natural frequency of the offshore wind turbine is important to ensure structural safety and power generation efficiency. Analytical studies so far proved that soil stiffness and foundation types affect the natural frequency of the offshore wind turbine. However, few experimental works on this subject have been done to complement and calibrate the results to meet actual site requirements. The purpose of this research is to investigate the influence of soil-foundation-structure interaction (SFSI) on the natural frequency of a wind turbine using geotechnical centrifuge experiment and to verify results with analytical methods based on existing codes. The natural frequency of the offshore wind turbine was evaluated under a fixed-base condition as well as SFSI condition using monopile and monopod foundations. Natural frequency reduction due to SFSI was experimentally obtained for both types of foundations. The test results were compared with theoretical analysis for cross-verification. The results demonstrated the specific effect of the soil stiffness and foundation type on the natural frequency of the offshore wind turbine.

Keywords: Offshore wind turbine, Natural frequency, soil-foundation-structure interaction, Geotechnical centrifuge test

RESUMÉ: Une évaluation précise de la fréquence naturelle des éoliennes offshore est importante pour assurer la sécurité structurelle et l'efficacité de la production énergétique. Jusqu'à présent, les études analytiques ont montré que la rigidité du sol et les types de fondations influent sur la fréquence naturelle des éoliennes offshore. Cependant, peu de travaux expérimentaux sur ce sujet ont été réalisés pour compléter et calibrer les résultats afin de répondre aux exigences réelles du site. Le but de cette recherche est d'étudier l'influence de l'interaction sol-fondation-structure (ISFS) sur la fréquence naturelle d'une éolienne à l'aide d'expériences de centrifugeuse géotechnique et de vérifier les résultats à l'aide de méthodes théoriques basées sur des codes existants. La fréquence naturelle des éoliennes offshore a été évaluée dans des conditions de base fixe ainsi que dans des conditions d’ISFS utilisant des fondations monopieu et monopode. La réduction de fréquence naturelle due à l‘ISFS a été obtenue expérimentalement sur les deux types de fondations, et les résultats des tests ont été comparés aux analyses théoriques par vérification croisée. Ces résultats montrent l’effet spécifique de la rigidité du sol et du type de fondation sur la fréquence naturelle des éoliennes offshore.

Mots clés: Éolienne offshore, fréquence naturelle, interaction sol-fondation-structure, essai de centrifugeuse géotechnique

1 INTRODUCTION

The size of offshore wind turbines continues to increase since the cost efficiency of the offshore wind turbine increases with its size. As the size and cost of offshore wind turbines increases, securing the structural stability of wind turbines against dynamic loads is one of the important problems. The flexible structure of the wind turbine is vulnerable to the dynamic load (Haritos, 2007), and the resonance vibration could reduce the efficiency of the generator and even causes damage to the structure. With the introduction of the variable speed wind turbine, the frequency bandwidth of the structural load spreads and the permissible natural frequency bandwidth of the offshore wind turbine becomes narrow (Kourkoulis et al. 2014). Due to these reasons, it is important to estimate the exact natural frequency of the wind turbine.

Conventionally, numerical analysis is used to evaluate this subject. Simplified spring-damper models were suggested by previous researches to conveniently evaluate the natural frequency. Still, an experimental approach is needed to supplement and calibrate the analytical results for consideration of the effect of SFSI in actual field condition. The geotechnical centrifuge can replicate field stress condition in model scale (Kim et al. 2013), and it can produce reliable experimental results while providing easy repeatability compared to a full-scale experiment. Therefore, it can be considered as an alternative method to overcome the limitations of full-scale experiments.

The purpose of this research is to evaluate the influence of SFSI on the natural frequency of offshore wind turbine using a geotechnical centrifuge experiment and to verify the test results by comparison with analytical results. A scaled model of a wind turbine tower and three foundations (one monopile and two monopod type foundations) were produced, and centrifuge tests were conducted to evaluate natural frequencies under both fixed and SFSI conditions. Changes in natural frequencies between fixed and SFSI conditions were evaluated, and the results were compared with theoretical solutions for a crosscheck. Natural frequency reduction was theoretically calculated by using equations suggested in FEMA-440 (FEMA, 2005).

2 CENTRIFUGE EXPERIMENT

Centrifuge experiment can raise the level of confinement to real field condition for the reduced scale model by applying centrifugal force. Hence, the precise simulation of field soil behaviour can be achieved by using centrifuge modelling in geotechnical experiments. The result of centrifuge experiment can be converted into the field scale by using centrifuge scaling laws. The scaling laws that correlate ng scaled model to 1g field model (prototype) are described in Table 1 (Schofield et al. 1980).

Table 1. Centrifuge scaling law

Parameters	Scaling factor
Length	1/N
Velocity	1
Acceleration	N
Time / Period	1/N
Frequency	N
Mass	$1/N^3$
Force	$1/N^2$

3 MODEL PRODUCTION

1/4 scaled National Renewable Energy Laboratory (NREL) 5MW wind turbine was used as a prototype model for scaled model production. The target structure was simplified to a flagpole model (van der Tempel & Molenaar, 2002). In the simplified model, the head structure, which includes blade, nacelle, and gearbox, is simplified into a lumped mass at the top, and the tower structure is simplified into a thin pipe. The model was scaled down for a 44g acceleration geotechnical centrifuge test following the scaling law.

Towere height (mm)	500
Towere diameter (mm)	36
Tower thickness (mm)	3
Head height (mm)	50
Head diameter (mm)	60

Figure 1. A scaled model of offshore wind turbine

Picture and dimension of the produced offshore wind turbine model are presented in Figure 1.

Three foundation models sharing the same offshore wind turbine model was produced for the experiment to compare the variation in natural frequency with foundation type. Foundation models are composed of two parts, substructure part (structure above the ground level) and installation part (structure below the ground level). Monopod-1 is a single bucket foundation without substructure, produced to observe the effect of SFSI on a monopod foundation. The Monopile is a single pile foundation with substructure, and Monopod-2 is a single bucket foundation with substructure.

To specifically compare the effect of SFSI minimizing the effect of structural aspect to natural frequency, the substructure of Monopod-2 foundation model was designed to have similar structural stiffness with a substructure of Monopile foundation model. For this, the substructure of Monopod-2 was designed to have the same height, mass, and centre of mass with a substructure of Monopile while maintaining its shape.

All three models were tested for two different base conditions (fixed-based and SFSI). In fixed-based condition, the model's substructure is directly connected with a rigid base plate to evaluate wind turbine's natural frequency without considering SFSI. In SFSI condition, full foundation model is installed into the model soil layer to evaluate wind turbine's natural frequency considering SFSI. Schematics and pictures of produced foundation models are given in Figure 2.

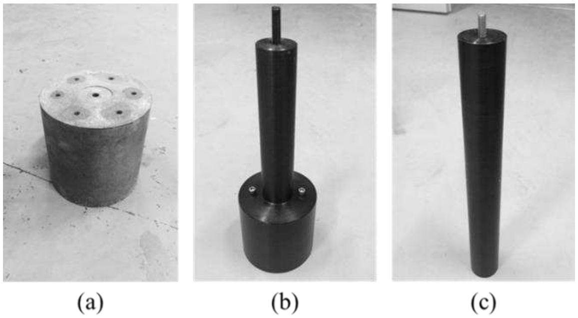


Figure 2. Foundation models (a) Monopod-1, (b) Monopod-2, (c) Monopile

4 FIXED-BASED TEST

1 g scaled model test in fixed-based condition was conducted to evaluate the wind turbine's natural frequency without considering SFSI. To reproduce fixed-based condition, the wind turbine model with a substructure of Monopile and Monopod-2 foundations were bolted on a rigid base plate. As the Monopod-1 model does not have a substructure, the fixed-based test was done by directly attaching the wind turbine model onto the base plate. Accelerometers were attached to the tower head to measure the time response of the structure. Detailed schematics of fixed-based test setups are described in Figure 3. Base conditions, sensor locations, and impact test conditions are identical for all three fixed condition test.

Fixed-based condition natural frequency was evaluated by an impact hammer test.

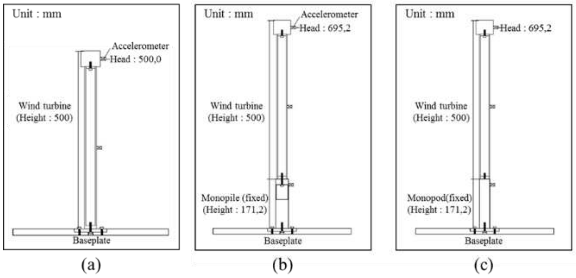


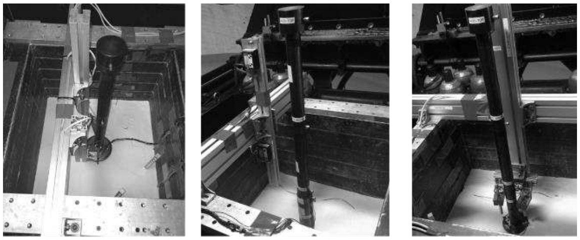
Figure 3. Schematics of fixed-based test for (a) Monopod-1, (b) Monopile, (c) Monopod-2

Acceleration response was used for the analysis. The recorded acceleration time history was converted into the frequency domain by using fast Fourier transformation (FFT). The Natural frequency was evaluated by peak-picking from the acceleration frequency response spectra. The result was converted to represent the prototype by using the scaling law.

5 SFSI CONDITION TEST

Centrifuge test in SFSI condition was carried out in a centrifugal acceleration field of 44 g to evaluate a natural frequency of wind turbine considering SFSI condition. To generate SFSI conditions, a 30 cm silica soil layer with a relative density of 85% was produced using air pluviation method. Five sets of bender element arrays were installed at each 6 cm depth to measure shear wave velocity. Bender elements were fixed in parallel aluminum bars (Ha et al. 2014). Foundation model was installed into the model soil layer; then the tower model was connected to the foundation model by bolting. The accelerometer was attached to the tower head to measure the time response. Soil condition and sensor installations are identical for all three SFSI condition tests; only foundation types are different. Photos from the SFSI condition test are provided in Figure 4.

A shear wave velocity profile was acquired by bender element tests. Shear wave travel time was picked by using the peak-to-peak measuring method.



(a) (b) (c)

Figure 4. Pictures from a SFSI test for (a) Monopod-1, (b) Monopile, (c) Monopod-2 Foundation.

Obtained shear wave velocity profiles were then used to calculate the soil's Young's modulus using equation (1) and (2).

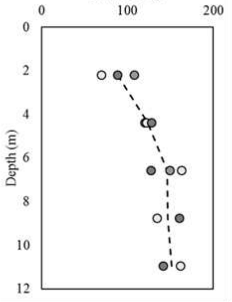
$$G_{max} = \rho \mathrm{v}_s{}^2 \tag{1}$$

$$E_{max} = 2G_{max}(1 + \nu) \tag{2}$$

Small-strain shear modulus (G_{max}) and small-strain Young's modulus (E_{max}) were used for the evaluation. The Soil density (ρ) was measured as 1580kg/m^3, and Poisson's ratio was assumed as 0.25. Figure 5 shows the variation in Young's modulus with soil depth acquired from bender element test.

The test was conducted for more than 10 minutes after the centrifuge spun up to 44g centrifugal acceleration to stabilize the soil condition due to the increased centrifugal force. The natural frequency of wind turbine in SFSI condition was evaluated by applying low amplitude (0.02~0.03g) frequency sweep using a centrifuge mounted shaking table (Seong et al. 2017).

Two types of frequency sweep signals were applied: 1) A low-to-high frequency sweep signal of 30~300 Hz, 2) A reverse high-to-low frequency sweep signal of 300~30 Hz. Each signal was applied at the bottom of the model box. The time and frequency records of input signals are shown in Figure 6.



Depth (m)	E_{max} (Mpa)
2.2	88.7
4.4	123.3
6.7	146.3
8.9	147.3
11.0	151.5

Figure 5. Variations in Young's modulus of soil with depth

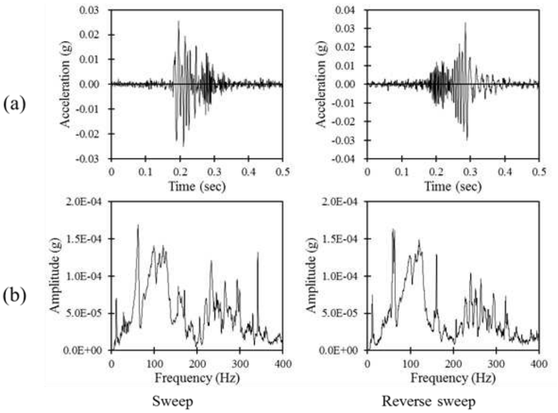


Figure 6. (a)Time,(b) frequency history of the input signal

Time response measured from the tower head accelerometer was used for the analysis. The measured data was processed in the same manner as the data from the fixed-based test.

6 THEORETICAL CALCULATION

The natural frequency of the OWT model considering SFSI was calculated based on theoretical methods suggested by existing codes (DNV, 2007 and FEMA, 2005) to crosscheck the experiment result. The relationship between foundation stiffness and natural frequency reduction can be described in equation (3) (FEMA, 2005). To calculate natural frequency reduction ratio between unfixed and fixed conditions, the effective stiffness of fixed-based structure (k^*_{fixed}), the effective height (h), as well as the foundation spring stiffness for the horizontal (k_x) and rotational (k_θ) component need to be evaluated.

$$\frac{f_n}{f_{n,fixed}} = \frac{1}{\sqrt{1+\frac{K^*{}_{fix}}{k_x}+\frac{K^*{}_{fix}h^2}{k_\theta}}} \tag{3}$$

The effective stiffness K^*_{fixed} was evaluated using equation (4) (FEMA, 2005). The effective mass (M^*) and stiffness (k^*_{fixed}) of the structure were estimated by performing an impact test with known added mass and solving equation 5 and 6 (Kim et al. 2014). f_1 is the natural frequency of structure and f_2 is the natural frequency of structure with added mass Madd at the head of structure. M^* and K^*_{fix} can be obtained by solving the simultaneous equation.

$$k^*{}_{fixed} = M^*(\frac{2\pi}{T})^2 \tag{4}$$

$$f_1 = \frac{1}{2\pi}\sqrt{\frac{k^*{}_{fix}}{M^*}} \tag{5}$$

$$f_2 = \frac{1}{2\pi}\sqrt{\frac{k^*{}_{fix}}{M^*+M_{added}}} \tag{6}$$

Effective height (h) is defined as the vertical distance from base to the centroid of first mode shape. A theoretical evaluation method for the stiffness of the monopile foundation is presented in Eurocode 8 (Eurocode, 2004); where they are evaluated by using equation (7) and (8) (Gazetas, 1984).

$$\frac{K_x}{dE_s} = 0.79\left(\frac{E_p}{E_s}\right)^{0.28} \tag{7}$$

$$\frac{K_\theta}{d^3E_s} = 0.15\left(\frac{E_p}{E_s}\right)^{0.77} \tag{8}$$

Horizontal (k_x) and rotational (k_θ) spring stiffness was calculated using Young's modulus of the pile (E_p), Young's modulus of soil (E_s), and pile diameter (d). Young's modulus of soil was evaluated at the soil depth the same as the monopile diameter.

The stiffness of the monopod foundation was calculated by simplifying the foundation into a shallow foundation model. Theoretical evaluation method for the spring stiffness of the circular embedded foundation was presented in DNV-OS-J101. In equation (9) and (10) (DNV, 2007), Horizontal (k_x) and rotational (k_θ) spring stiffness components were calculated using soil's shear modulus (G), radius of foundation (R), depth to bedrock (H), foundation embedded depth (D), and Poisson's ratio (v). In this calculation, shear modulus was evaluated at the soil depth the same as the monopod diameter.

$$k_x = \frac{8GR}{2-\nu}\left(1+\frac{R}{2H}\right)\left(1+\frac{2}{3}\frac{D}{R}\right)\left(1+\frac{5}{4}\frac{D}{H}\right) \tag{9}$$

$$k_\theta = \frac{8GR3}{3(1-\nu)}\left(1+\frac{R}{6H}\right)\left(1+2\frac{D}{R}\right)\left(1+0.7\frac{D}{H}\right) \tag{10}$$

By using k^*_{fix}, h, k_x, and k_θ calculated for each foundation system, the natural frequency reduction ratio can be calculated. The natural frequency of an offshore wind turbine considering SFSI can be calculated by multiplying natural frequency reduction ration to the fixed-based natural frequency evaluated in a fixed-based impact hammer test.

7 RESULTS AND DISCUSSIONS

The natural frequency of offshore wind turbine in fixed-based condition was evaluated through the FFT of the acceleration time-series, which were obtained by the accelerometer attached to the hub of the wind turbine. The result was converted using scaling laws to represent the prototype. The result gave a natural frequency of 1.05Hz for the Monopod-1 case, 0.72Hz for the Monopod-2 case, and 0.74Hz for the Monopile case. Monopod-2 and the Monopile showed a similar natural frequency with the fixed-base condition. Considering that the natural frequency is affected by mass and stiffness, and the weight of both structures is the same, these two structures can be considered to have similar structural stiffness.

Natural frequency evaluated in SFSI condition centrifuge test was compared with the result of the fixed-based scaled model test result. Figure 7 shows the comparison between natural frequency evaluated in fixed-based condition by using an impact test, and the natural frequency evaluated for SFSI conditions by using sweep and reverse sweep signals. Both results were converted using the scaling laws to represent the prototype. Acceleration intensities were normalized by the ratio of the peak for more visible comparison. Results showed apparent natural frequency reduction for all three foundations.

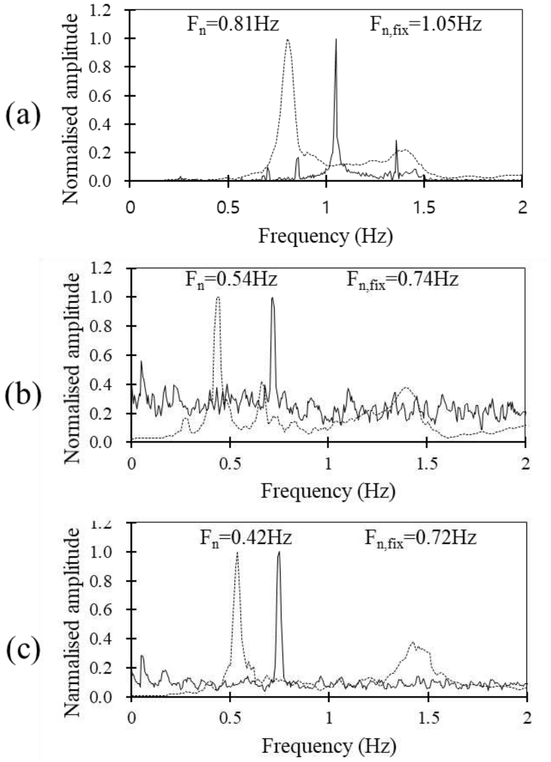


Figure 7. Fixed-based and SFSI condition natural frequency for (a) Monopod-1, (b) Monopile, (c) Monopod-2 foundation

In the case of Monopod-1, the natural frequency decreased from 1.05Hz (for fixed-based condition) to 0.81Hz. In the case of Monopod-2, the natural frequency decreased from 0.72Hz to 0.42Hz. In the Monopile case, the natural frequency decreased from 0.74Hz to 0.54Hz.

Table 3. shows a comparison between the calculated and measured natural frequency of offshore wind turbine for each foundation types. Both experimental and theoretical approach showed a certain effect of SFSI to the natural frequency of OWT. Calculation results match the experimental results with less than 10% error. The results suggest that analytical calculations based on existing codes can be used to evaluate

the natural frequency of offshore wind turbine considering SFSI.

Although Monopile and Monopod-2 case shared same weight and height and the fixed natural frequency for both cases showed only 3% difference, both experimental and theoretical result showed that the natural frequency of an offshore wind turbine with monopile foundation is 20% higher than for the Monopod-2 foundation. Considering that the monopile case showed about twice as high horizontal spring stiffness and three times higher rotational spring stiffness than the Monopod-2 case, it can be considered that the difference in foundation spring stiffness related to the different foundation types influenced the natural frequency of offshore wind turbine system.

Table 3. Calculated and measured natural frequency considering SFSI

	Calculated	**Measured**
Monopod-1	0.71 Hz	0.81 Hz
Monopile	0.56 Hz	0.54 Hz
Monopod-2	0.37 Hz	0.42 Hz

8 CONCLUSIONS

The goal of this research was to evaluate the effect of SFSI on the natural frequency of a wind turbine for monopile and monopod foundation types and cross-verify the result by comparing the results from a centrifuge experiment with analytical calculation. Experimental results show a clear effect of SFSI toward the natural frequency of wind turbine structure by foundation types. Case study comparison between the monopile and the monopod foundation with the same mass and fixed structural stiffness showed that the monopile foundation showed stiffer behaviour than the monopod. Theoretical evaluation based on existing codes matched the experimental results within a 10% error margin.

Overall, the results of this study show that the effect of SFSI needs to be considered when estimating the natural frequency of offshore wind turbines, and the natural frequency reduction due to SFSI can be evaluated by using centrifuge modelling as well as analytical evaluation with appropriate soil and foundation data

9 ACKNOWLEDGEMENTS

This work was supported by the New & Renewable Energy of the Korea Institute of Energy Technology Evaluation and Planning (KETEP) grant funded by the Korea government Ministry of Trade, Industry and Energy. (No. 20143010024330, SUCCESS project)

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