

Numerical study of soil-structure interaction effects on the natural frequency of offshore wind turbines

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Abstract:

Offshore wind turbines (OWT) are considered one of the most promising ways of harvesting green energies in the world. OWTs are dynamically sensitive as their loading frequency is close to their natural frequency, allowing a narrow frequency band to avoid resonance. Therefore, precise estimation of their natural frequency (f_n) can be crucial. Soil-structure interactions (SSI) can be of great importance in the estimation of dynamic characteristics of OWTs. In this study, a standard offshore wind turbine is modeled using FLAC-3D in two cases of fixed-base, i.e., with no SSI, and another case with an entire system of soil and structural parts to estimate the effects of SSI on the natural frequency of the OWT systems. The result showed that modeling the OWT in the fixed base state results in an overestimation of the natural frequency of the system by 20 percent, which can be misleading in the design process. In addition, the damping ratio was largely underestimated in the fixed base condition due to the main contribution of soil damping. Therefore, the importance of soil-structure interactions was emphasized in the modeling and design of offshore wind turbines.

1. Introduction

Offshore wind turbines (OWTs) have attracted a lot of attention as one of the most promising means of harvesting green energies. Every year, more investments are made in development and optimization of offshore wind turbines. The wind farm industry is growing by increasing the larger turbines, taller towers, and deeper installation in seabed to achieve more efficiency of energy production. Increasing the size and cost of OWTs demands securing their structural integrity in the harsh offshore environment [1]. Offshore wind turbines are sensitively dynamic structures, as their natural frequency is close to their loading frequency. Due to the special structural shape, i.e., a combination of a long slender column with a heavy mass on top, a low natural frequency results in OWTs falling within the range of 0.3-0.5 Hz [2]. On the other hand, the frequencies of service loads, which are mainly comprised of environmental loads of wind and wave thrust, are applied in the same range of

frequencies. The wind load is applied at the rotor with a frequency in the range of 0.12-0.3 Hz [2], called the 1P. The passing of the blades across the tower induces a cyclic load, called the shadowing effect, with a frequency of 3P (number of blades multiplied by the 1P frequency), in the range of 0.35-0.9 Hz [2]. This condition makes the OWTs susceptible to resonance and excessive increase of dynamic loads, which can lead to damage to the OWTs. Subsequently, design codes such as DNV [3] and GL [4] impose strict regulations to keep the first global natural frequency of the system at least ∓ 10 percent away from the 1P and 3P frequencies. This implies a relatively narrow frequency band to be allowed. In addition, the natural frequency of the system is of great importance in the fatigue design of OWTs as an OWT experiences millions of cycles in a life span of 20 years [5]. Moreover, future changes in the system stiffness, such as variations in soil stiffness, can affect the natural frequency of the system, leading to a violation of the allowed frequency band [6, 7]. Therefore, special care should be taken to avoid resonance by keeping a safe distance between the loading frequencies and the natural frequency of the OWT. There are

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three options to tackle this design issue, called the soft-soft (placing f_n before 1P), soft-stiff (placing f_n between 1P and 3P), and stiff-stiff approaches (placing f_n after 3P), as depicted by Figure 1. As a result, precise estimation of natural frequencies of the OWTs, especially the 1st/first mode, is of great importance. Recent studies showed the crucial effect of soil-structure interactions on the dynamic characteristics of OWTs [8-13]. In this regard, Seong et al. [14], using a centrifuge study, showed a 30 percent decrease in natural frequency in the SSI condition compared to the fixed base state.

The soil-structure interactions can be modelled using various methods from simplified analytical models to advanced numerical analyses. Spring models in terms of non-linear p-y springs are widely used due to their advantage of low computational cost. However, they have some shortcomings, such as non-realistic modelling of damping, incapability of modelling pore water pressure generation, etc. [2]. Nevertheless, numerical modelling, using advanced non-linear constitutive models, is becoming more popular due to the precise simulation of the problem by bridging between the micro-element mechanisms to macro-structure behaviour [15].

In this study, the natural frequency of a standard offshore wind turbine is estimated using three-dimensional numerical modelling in two cases of inclusion of SSI and the case of exclusion of SSI (i.e., in the fixed base state). Two models were built, one in the fixed base state with no influence of soil-structure interaction, and the other with soil and foundation, considering the SSI.

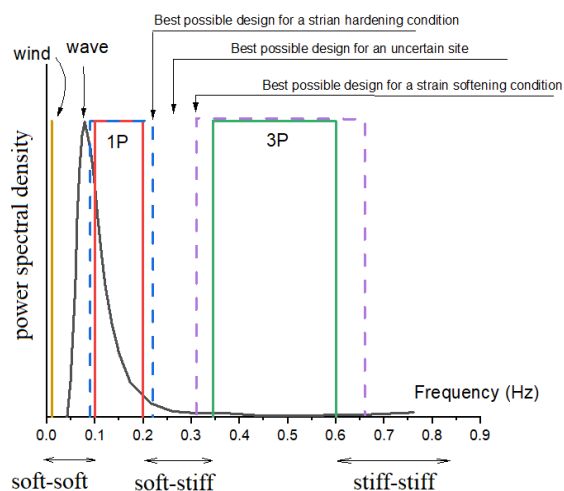


Fig. 1: Loading frequencies and possible design options in OWTs [16]

2. Numerical model

In this study, FLAC-3D was used for numerical modeling.

This program is a finite difference program capable of solving complex dynamic problems. The NREL-5MW

turbine with the listed parameters in Table 1[17] was adopted/used for modeling. The built model is shown in Figure 2. The modeling procedure included the following steps: First, geometry of the model, including the soil and the structural parts (i.e., the monopile, the tower, and the rotor-nacelle-assembly), was built by generating the grids. The in-situ state was set by establishing the initial stresses and pore water pressures. The construction stage was modeled using the wished-in-place approach by replacing the materials of the monopile and assigning appropriate properties (linear elastic model with elastic modulus of 210 GPa, Poisson's ratio of 0.2, and mass density of 7800 kg/m²) to the structural parts. The rotor-nacelle-assembly (RNA) was modeled as a lumped mass at the top of the tower with equivalent mass density to represent its total mass. However, to avoid stress concentration, the lumped mass was modeled as a hollow cylinder as the continuation of the tower. Afterwards, the model was brought to an equilibrium due to the construction loads. Finally, the model was run in the dynamic mode for the free vibration test, as described in the next section.

The size of the model was set as five times the monopile diameter in the horizontal direction [18, 19], and twice its length in the vertical direction. Free field boundaries were adopted in the dynamic mode to eliminate the spurious waves returning along the side boundaries. Three interface layers were used to govern the soil-monopile contact interactions for the inner and outer walls of the monopile as well as for the top lid of the monopile.

Damping modeling in OWTs is a controversial issue as there are different sources of damping of different natures. There are different damping contributors in an OWT system, including the tower oscillation damping, the damping caused by the steel structure, the aerodynamic damping, the hydrodynamics damping, and most importantly, the soil damping. The total damping is estimated to be 7-10 % in the service state and 1-3 % in the parked state [20, 21]. In this study, the soil damping was merely taken into consideration as it has the most contribution in total damping [21].

The hysteretic damping of soil was considered by adopting the non-linear constitutive model of SANISAND [22]. This model is an advanced plasticity model with bounding surface plasticity using the critical state soil mechanics and the state parameter. The model has been developed numerously, especially by adding a memory surface [15, 23-28]. The adopted model parameters are presented in Table 2, calibrated by Eslami and Ghorbani [29]. However, a 0.5 percent of Rayleigh damping was also considered to damp the high-frequency spurious components, as suggested by Itasca [30].

Table 1: Properties of NREL-5MW wind turbine [17] and the monopile foundation modeled in this study

Property	Value
Rating	5 MW
Rotor orientation, configuration	Upwind, 3 blades
Rotor diameter, hub diameter	126 m, 3 m
Hub height	90 m
Cut-in, rated, cut-out wind speed	3 m/s, 11.4 m/s, 25 m/s
Cut-in, rated rotor speed	6.9 rpm, 12.1 rpm
Rated tip speed	80 m/s
Rotor mass	110 Ton
Nacelle mass	240 Ton
Tower mass	347.466 Ton
Tower height	87.6 m
Tower top diameter, wall thickness	3.87 m, 0.019 m
Tower base diameter, wall thickness	6 m, 0.027 m
Substructure base diameter, wall thickness	6 m, 0.06 m
Support structure steel density	8500 kg/m ³
Steel Young's modulus	210 GPa
Monopile Diameter, length, and wall thickness	6m, 27 m, 0.04 m

Table 2: SANISAND model parameters used in this study [29]

Parameter	Value
Elasticity	
Elastic material constant (G_0)	145
Poisson's ratio (ν)	0.05
Critical-state stress	
Critical-state stress ratio (M)	1.35
The ratio of critical-state stress ratio in extension and compression (c)	0.70
State line constant (λ_c)	0.019
Void ratio at $p=0$ (e_0)	0.934
State line constant (ξ)	0.70
Yield surface constant (m)	0.0.1
Plastic modulus	
h_0	8.40
c_h	0.968
n^b	1.20
Dilatancy	
A_0	0.704
n^d	3.5
Fabric-dilatancy tensor parameters	
z_{max}	7.50
c_z	625
Overshooting correction	
\bar{e}_p	0.01
e_p	1

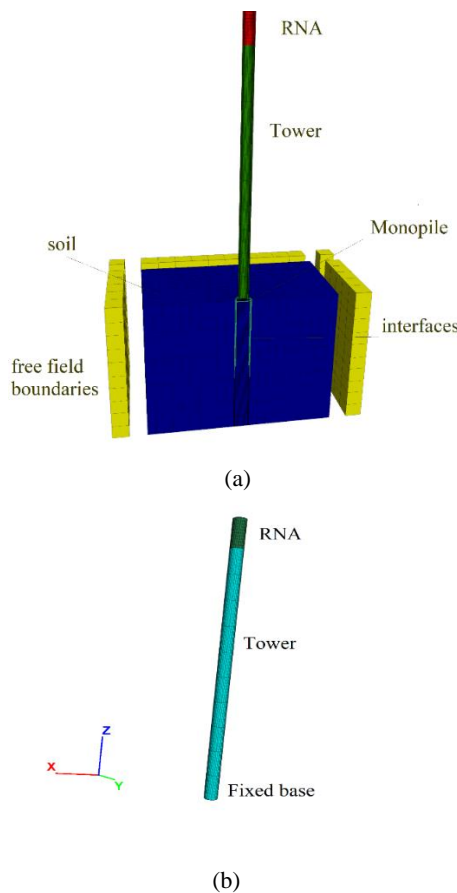


Fig. 2: Numerical models built in this study; a) the full model including the SSI, b) the fixed base state excluding the SSI

3. Free vibration Test

After reaching equilibrium in the construction stage, the mode is ready for the free vibration test in the dynamic mode. The static boundary conditions were modified by removing the horizontal constraints, and the free-field boundaries were activated. The model was allowed to vibrate in the dynamic mode on its own weight. The vibrations were recorded at the top of the tower as a time history of displacements. The records were transferred into the frequency domain by the Fourier transform (FFT). The natural frequencies of the models were estimated by inspecting the peaks of the Fourier spectrum.

4. Results

Figure 3 (a) presents the results of the free vibration test as time histories of horizontal displacements of the tower at the hub level for the two cases of SSI-included (full system) and

SSI-excluded (fixed base). Furthermore, Figure 3 (b) presents the results in the frequency domain obtained by the Fourier transform. As can be observed/seen, the natural frequency of the system was obtained as 0.39 Hz in the SSI case and 0.48 Hz in the fixed base case. This means that a lower natural frequency of at least 20% is obtained by considering the soil and foundation as well as related interactions. This is in fair agreement with Seong et al. [14], in which a 30 percent decrease in natural frequency in the SSI condition was obtained compared to the fixed base state. Due to the level of precision required in the estimating the first natural frequency of the OWT systems, and the narrow-allowed frequency band of design, it can be concluded that considering soil-structure interactions is crucial in the design and analysis of OWTs.

In addition, the total damping ratio (ζ) was estimated using the logarithmic decrement (δ), using the following relationships:

$$\delta = \frac{1}{n} \ln \left(\frac{A_0}{A_n} \right) \tag{1}$$

$$\zeta = \frac{1}{\sqrt{1 + \left(\frac{2\pi}{\delta} \right)^2}} \tag{2}$$

Where A_0 is the initial amplitude of interest, and A_n is the final amplitude of interest, and n is the number of peaks calculated in a period of the signal. As can be seen in Figure3 (a), a much higher damping is observed in the SSI case compared to that of the fixed base state, represented by more decrease in oscillation amplitudes. The damping ratio was estimated as 11 % in the SSI case and 4 % in the fixed base state. Therefore, it can be concluded the effect of soil-structure interaction is of great importance in estimating the damping of the OWT system, as soil damping is the main contributor in the total damping of the OWT system.

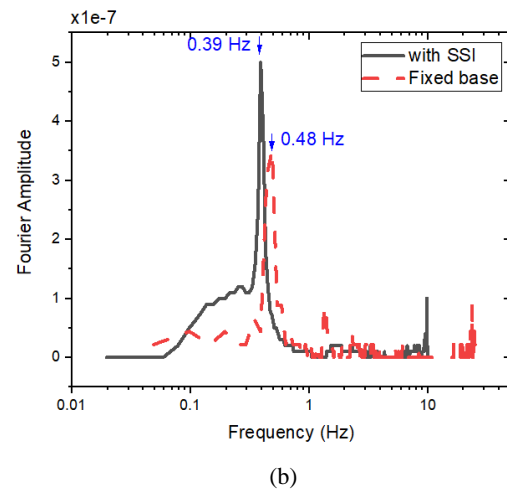
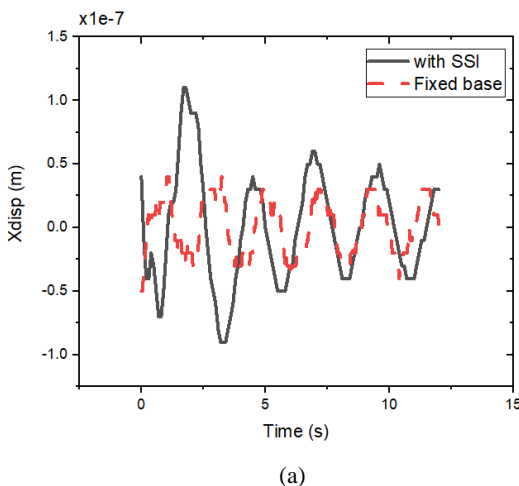


Fig. 3: Results of free vibration test; a) time history of displacements at the hub level, b) Fourier transform of the response

5. Conclusion

In this study, the importance of soil-structure interactions (SSI) on the dynamic characteristics of offshore wind turbines (OWTs) was manifested by numerical modeling. Two cases of numerical models were built in the fixed base state and in the case of modeling the entire system of soil, foundation, and the structural parts to include the soil-structure interactions. It was found modeling the OWT in the fixed-base state overestimates the first natural frequency of the system by 20 percent due to the effects of soil-structure interactions. This can be considered critical due to the dynamic sensitivity of OWTs, which allows only a narrow band of natural frequency in design. Moreover, the damping ratio was underestimated in the fixed base state, emphasizing the importance of soil-structure interactions in the design and analysis of offshore wind turbines.

References

[1] Wang X, Zeng X, Li J, Yang X, Wang H. A review on recent advancements of substructures for offshore wind turbines. Energy conversion and management. 2018;158(103-19).

[2] Kaynia AM. Seismic considerations in design of offshore wind turbines. Soil Dynamics and Earthquake Engineering. 2019;124(399-407).

[3] DNV. Design of offshore wind turbine structures. DET NORSKE VERITAS. 2014;DNV-OS-J101(

[4] GL. Guidline for the certification of wind turbines. Germanischer Lloyd, 2010.

[5] Bhattacharya S. Challenges in design of foundations for offshore wind turbines. Engineering & Technology Reference. 2014;1(1):922.

[6] Bhattacharya S, Biswal S, Aleem M, Amani S, Prabhakaran A, Prakhya G, et al. Seismic Design of Offshore Wind

- Turbines: Good, Bad and Unknowns. *Energies*. 2021;14(12):3496.
- [7] Bhattacharya S, Cox JA, Lombardi D, Muir Wood D. Dynamics of offshore wind turbines supported on two foundations. *Proceedings of the Institution of Civil Engineers-Geotechnical Engineering*. 2013;166(2):159-69.
- [8] Adhikari S, Bhattacharya S. Vibrations of wind-turbines considering soil-structure interaction. *Wind and Structures*. 2011;14(2):85.
- [9] AlHamaydeh M, Hussain S. Optimized frequency-based foundation design for wind turbine towers utilizing soil-structure interaction. *Journal of the Franklin Institute*. 2011;348(7):1470-87.
- [10] Bhattacharya S, Adhikari S. Experimental validation of soil-structure interaction of offshore wind turbines. *Soil Dynamics and Earthquake Engineering*. 2011;31(5-6):805-16.
- [11] Kj rtaug RA, Kaynia AM. Vertical earthquake response of megawatt-sized wind turbine with soil-structure interaction effects. *Earthquake Engineering & Structural Dynamics*. 2015;44(13):2341-58.
- [12] Lombardi D, Bhattacharya S, Wood DM. Dynamic soil-structure interaction of monopile supported wind turbines in cohesive soil. *Soil Dynamics and Earthquake Engineering*. 2013;49(165-80).
- [13] Shi W, Park HC, Chung CW, Shin HK, Kim SH, Lee SS, et al. Soil-structure interaction on the response of jacket-type offshore wind turbine. *International Journal of Precision Engineering and Manufacturing-Green Technology*. 2015;2(2):139-48.
- [14] Seong JT, Ha JG, Kim JH, Park HJ, Kim DS. Centrifuge modeling to evaluate natural frequency and seismic behavior of offshore wind turbine considering SFSI. *Wind energy*. 2017;20(10):1787-800.
- [15] Liu H. Constitutive modelling of cyclic sand behaviour for offshore foundations: Delft University of Technology, 2020.
- [16] Bhattacharya S, Nikitas N, Garnsey J, Alexander N, Cox J, Lombardi D, et al. Observed dynamic soil-structure interaction in scale testing of offshore wind turbine foundations. *Soil Dynamics and Earthquake Engineering*. 2013;54(47-60).
- [17] Jonkman J, Butterfield S, Musial W, Scott G. Definition of a 5-MW reference wind turbine for offshore system development. National Renewable Energy Lab.(NREL), Golden, CO (United States), 2009.
- [18] Esfeh PK, Kaynia AM. Numerical modeling of liquefaction and its impact on anchor piles for floating offshore structures. *Soil Dynamics and Earthquake Engineering*. 2019;127(105839).
- [19] Esfeh PK, Kaynia AM. Earthquake response of monopiles and caissons for Offshore Wind Turbines founded in liquefiable soil. *Soil Dynamics and Earthquake Engineering*. 2020;136(106213).
- [20] D las LD. Estimation of Soil Damping Contribution on Offshore Monopiles Using Plaxis 3D Approach: M.Sc. Thesis, Delft University of Technology, Netherland, 2018.
- [21] Malekjafarian A, Jalilvand S, Doherty P, Igoe D. Foundation damping for monopile supported offshore wind turbines: A review. *Marine Structures*. 2021;77(102937).
- [22] Dafalias YF, Manzari MT. Simple plasticity sand model accounting for fabric change effects. *Journal of Engineering mechanics*. 2004;130(6):622-34.
- [23] Barrero AR, Taiebat M, Dafalias YF. Modeling cyclic shearing of sands in the semifluidized state. *International Journal for Numerical and Analytical Methods in Geomechanics*. 2020;44(3):371-88.
- [24] Dafalias YF, Taiebat M. SANISAND-Z: zero elastic range sand plasticity model. *G otechnique*. 2016;66(12):999-1013.
- [25] Liu H, Diambra A, Abell JA, Pisan  F. Memory-enhanced plasticity modeling of sand behavior under undrained cyclic loading. *Journal of Geotechnical and Geoenvironmental Engineering*. 2020;146(11):04020122.
- [26] Taiebat M, Dafalias YF. SANISAND: Simple anisotropic sand plasticity model. *International Journal for Numerical and Analytical Methods in Geomechanics*. 2008;32(8):915-48.
- [27] Taiebat M, Jeremi  B, Dafalias YF, Kaynia AM, Cheng Z. Propagation of seismic waves through liquefied soils. *Soil Dynamics and Earthquake Engineering*. 2010;30(4):236-57.
- [28] Yang M, Taiebat M, Dafalias Y. SANISAND-MSf: a memory surface and semifluidized state enhanced sand plasticity model for undrained cyclic shearing. *G otechnique*. 2020;72(3):227-46.
- [29] Eslami A, Ghorbani A. Seismic response of offshore wind turbines supported on Monopiles and Suction Buckets: Numerical modelling and soft computing study. *Soil Dynamics and Earthquake Engineering*. 2022;159(107284).
- [30] Itasca. FLAC, Fast Lagrangian Analysis of Continua. USER'S GUIDE. 2015.



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