Abstract

Design of monopiles for multi-megawatt wind turbines at 50 m water depth

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Introduction

Recent advancements in wind energy allow larger size offshore wind turbines placed in greater water depths in the order of 50 m. To be cost effective, innovative designs are required that are easy to install and with long lifetime. One potentially applicable substructure design [1, 2] is a large diameter monopile, whose design envelope at 50 m water depth is to be evaluated. Since most monopiles installed today are at less than 30 m water depths, extrapolation of the current designs for the water depth to 50m depth is not straight forward, but it requires a design scheme which ensures structural integrity and feasibility of installation.

The aim of this study is to design a monopile foundation for a 10 MW wind turbine placed in 50 m water depth by considering both ultimate and fatigue stress limits from fully coupled load simulations. It accounts for the constructability aspect along with the material mass minimization and will also study the effect of the bottom tip modelling with respect to soil-structure interaction.

Approach

The 10 MW reference wind turbine [3] is considered as Class 1A, with relevant sea states and soil properties collected from INNWIND.EU [4]. The soil-structure interaction is modelled based on the Winkler approach [5] as recommended by design codes of the American Petroleum Institute [6] and Det Norske Veritas [7]. The hydrodynamic loads on large diameter monopiles are modelled using the Morison equation with corrected coefficients for diffraction as developed by [8]. The turbine and environmental parameters are implemented within the load-simulation software package HAWC2 [9].

Main body of abstract

The technical description of the wind turbine can be referenced from [3]. Figure 01 depicts the corresponding Campbell diagram of the wind turbine, which shows that 1P, 3P and 6P ranges are respectively in Hertz [0.099, 0.158], [0.300, 0.480] and [0.600, 0.960]. The expected normal sea states as per [4] are presented in Table 1.

As a starting point, the wind turbine is considered at a mean water depth of 26 m. A corresponding monopile is designed to fit the natural frequency criteria to avoid the excitation frequencies depicted in Figure 01. As a first trial, a pile of 7.5 m outer-diameter and 10 cm wall thickness is extruded from 26 m above mean water level till 50 m below the seabed i.e. a total of 102 m. The hub height above mean sea level is maintained as fixed at 119 m. Four steps were required to have the first natural frequencies out of resonant ranges by adjusting the outer diameter, wall thickness and embedment depth of the monopile. This process is summarized in Table 2 where lines in boldface represent those that have been selected and used in the next step. The re-design of the monopile is made based on the constructability and material mass minimization. The following conflicting design aspects are analysed:

- Larger outer diameter and smaller wall thickness lead to lighter piles and are easy to roll manufacture.

- Larger outer diameter leads to large bending stiffness, but also to higher wave loads.
- Smaller outer diameter leads to larger wall thickness and to deeper piles, but with reduced wave loading.

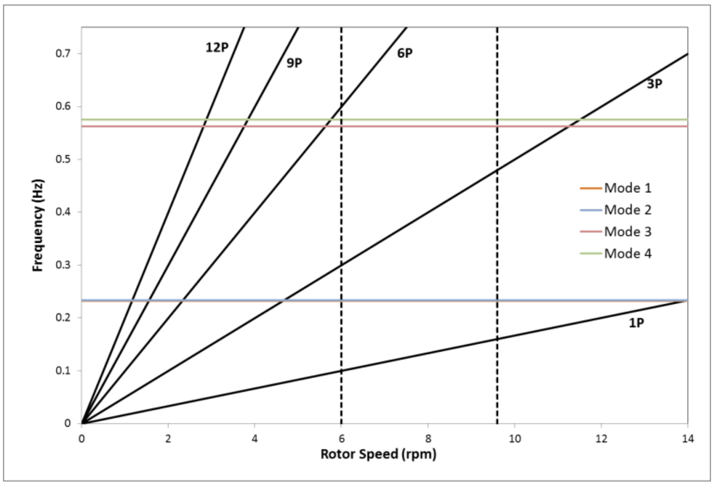

Figure 01. Campbell diagram of the proposed structure.

Table 1. Sea state [4]

Ws [m/s]	5	7	9	11	13	15	17	19	21	23	25
Hs [m]	1.140	1.245	1.395	1.590	1.805	2.050	2.330	2.615	2.925	3.255	3.654
Tp [s]	5.820	5.715	5.705	5.810	5.975	6.220	6.540	6.850	7.195	7.600	8.106

Where *Ws* stands for *Mean Wind Speed*; *Hs* for *Significant Wave Height* and *Tp* for *Peak Spectral Period*.

Based on the design results at 26 m water depth, a preliminary monopile for 50 m water depth has been estimated with 10.0 m outer diameter, 110 mm wall thickness, 50 m embedded depth, Tower B, joint type pile's tip. A similar tuning process has been carried out, and the corresponding results are collected in Table 3. At the process' end, tuned properties have been obtained: outer diameter: 9.50m; embedded depth: 30 m; wall thickness 110 mm. The corresponding natural frequencies are placed on Figure 01. The whole process containing cases for 26 and 50 m is illustrated on Figure 02.

Table 2. Tuning process for 26 m water depth

		Frequencies [Hz]			
		Mode 1	Mode 2	Mode 3	Mode 4
Step 1: tower geometric dimensions (OD = 7.5 m, WT = 0.10 m; SL = 50 m)	Tower A (M = 620,687 kg)	0.23	0.23	0.58	0.60
	Tower B (M = 644,026 kg)	**0.23**	**0.24**	**0.58**	**0.60**
Step 2: embedded pile depth below soil (OD = 7.5 m, WT = 0.10 m; SL = variable)	50 m	0.23	0.237	0.58	0.60
	30 m	**0.23**	**0.235**	**0.58**	**0.60**
	25 m	0.23	0.228	0.58	0.60
Step 3: pile's tip condition (OD = 7.5 m, WT = 0.10 m; SL = 30 m)	fully clamped	0.234	0.236	0.583	0.606
	joint type *(no heave, no yaw)*	**0.232**	**0.235**	**0.582**	**0.606**
Step 4: wall thickness (OD = 7.5 m, WT = variable; SL = 30 m)	80 mm	0.218	0.219	0.582	0.605
	100 mm	**0.232**	**0.235**	**0.582**	**0.606**

Table 3. Tuning process for 50 m water depth

		Frequencies [Hz]			
		Mode 1	Mode 2	Mode 3	Mode 4
Step 1: embedded pile depth below soil (OD = 10 m, WT = 0.11 m; SL = variable)	50 m	0.256	0.259	0.562	0.579
	30 m	**0.240**	**0.242**	**0.563**	**0.575**
	25 m	0.218	0.220	0.563	0.568
Step 2: Outer diameter (OD = variable, WT = 0.11 m; SL = 30 m)	10.0 m	0.240	0.242	0.563	0.575
	9.5 m	**0.232**	**0.233**	**0.563**	**0.575**
	9.0 m	0.222	0.224	0.562	0.574
Step 3: wall thickness (OD = 9.5 m, WT = variable; SL = 30 m)	102 mm	0.227	0.229	0.562	0.575
	106 mm	0.229	0.231	0.562	0.575
	110 mm	**0.232**	**0.233**	**0.563**	**0.575**

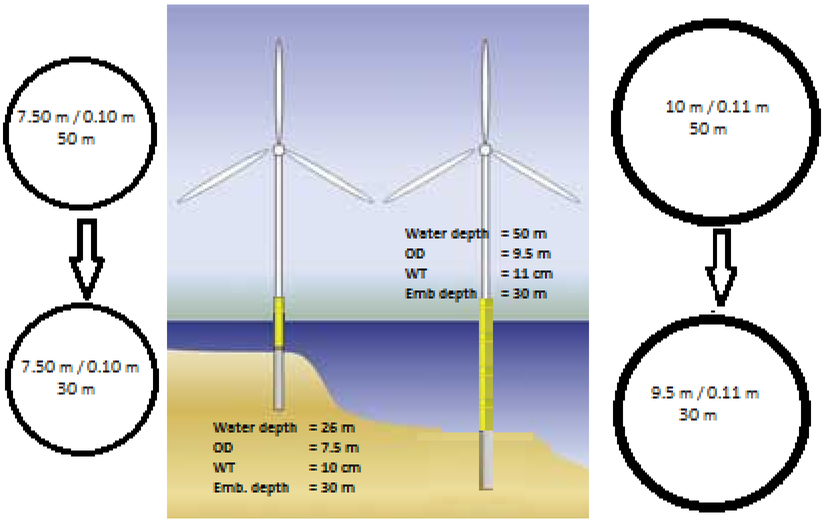

Figure 02. Design process.

Once the natural frequency target has been met, the resulting structure will be used for load calculations. Wave motions are considered along irregular airy theory supplemented with Wheeler stretching. The soil-structure interaction couples the vertical and lateral responses to the cyclic and dynamic loading [10]. Thus, the vertical skin friction (t-z curves) has been set dependent to the cyclic soil resistance (p-y curves). The initial confining pressure and the gapping phenomenon are accounted for.

The obtained load time histories will be used to determine the ultimate and fatigue limit state design loads and estimate the lifetime of the structure. Based on the results, the design of the structure may be optimized by redesigning with a more structurally robust cross-section or changes in the length of the pile inside the soil.

Conclusion

A feasible monopile for a 10 MW wind turbine placed in 50 m water depth will be designed. Realistic assumptions and constraints are defined and fulfilled and the structural integrity required by design standards will be satisfied. Further attention will be given to the influence of monopile boundary condition modelling below the soil. More studies will also be made on the interactions: (a) accounting for the initial pressure due to pile driving; (b) dynamic bilinear versus cyclic soil resistance; (c) presence or not of vertical skin friction; (d) coupling effect of p-y curves and t-z curves and; (e) gapping phenomenon.

Learning objectives

This study proposes a feasible monopile for multi-megawatt wind turbine placed in moderate water depths of 50 m. It proposes a design that has 25 years fatigue lifetime. It considers relevant constructability and material mass minimization. The influence of soil modelling is considered within the assumptions of the Winkler approach, as well as the importance of soil-structure modelling along different complexity levels.

Acknowledgements

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