First natural frequency of an offshore wind turbine founded on monopile: challenge and evaluation

L. Kerner[1], J. C. Dupla[1], G. Cumunel[1], J. Canou[1], J. M. Pereira[1], P. Argoul[2]

[1] Laboratoire Navier (IFSTTAR, CNRS, ENPC), France
[2] IFSTTAR, laboratoire MAST-EMGCU, France

1 Development of offshore wind turbine in Europe: dynamic challenge

The first offshore wind farms were installed in Northern Europe, which makes it the most developed region in the world regarding offshore wind turbines. Actually, 91% of the offshore wind farms are settled in North, Baltic and Ireland seas and in the English Channel. According to the 2016 annual report from WindEurope (2017), a total capacity of 12 631 MW is installed in Europe which represents 81 offshore wind farms, 3589 offshore wind turbines and, 10 countries. The distribution of these farms is presented in Fig. 1.

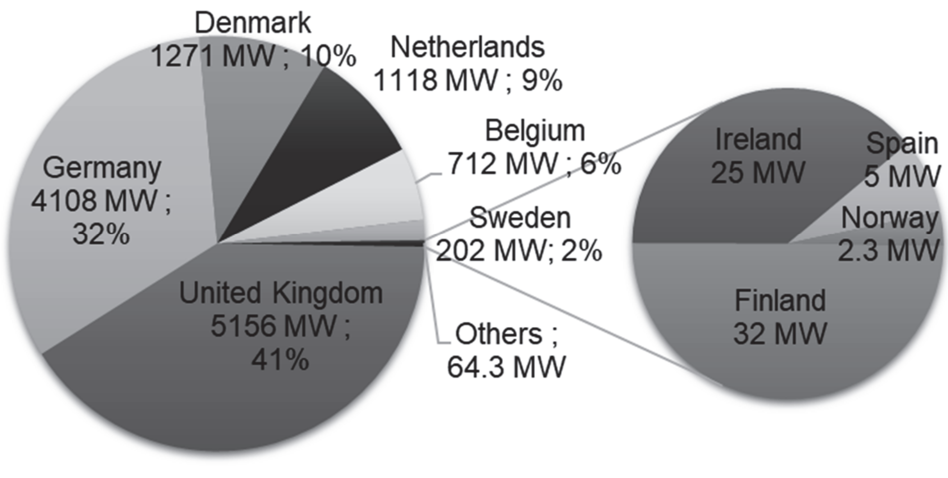


Fig. 1: Offshore wind turbines installed in Europe and their capacity in 2016 (windeurope.org)

An ambitious policy regarding renewable energies started in Europe, in 2008, after the 2020 climate and energy package, which defines three main goals:

- 20% reduction of the emission of green gas effect (in comparison to the levels in 1990);

- 20% integration of renewable energy in the European Union's energy consumption;
- 20% improvement of the energy efficiency.

In order to achieve the second goal, offshore wind energy has been strongly developed in the EU costal countries and this sector will keep on evolving with the increasing concern on sustainable development and climate change.

A typical offshore wind turbine (OWT) currently installed is submitted to various cyclic and dynamic loads: wind, waves and, currents with excitation frequencies below 0.2 Hz. Among these excitation frequencies, the rotor frequency (noted *1P*) and the passing blade frequency (noted *3P*) should also to be taken into account. A sum-up of these frequencies is presented in Fig. 2 for three existing offshore wind turbines (Vestas V90 3 MW, Siemens 6 MW, Vestas V164 8 MW) and a 5 MW standard offshore wind turbine defined by the NREL (Jonkman et al., 2009). To avoid any resonance phenomenon, an offshore wind turbine is designed in order to have its first natural frequency between the *1P* and *3P* intervals. This kind of turbine is called soft-stiff, i.e. a soft mast and a stiff foundation. Concerning the three existing offshore wind turbines (Fig. 2), the soft-stiff interval tends to reduce with the increasing capacity of the turbine. Therefore, it is essential to evaluate precisely the first natural frequency of the structure.

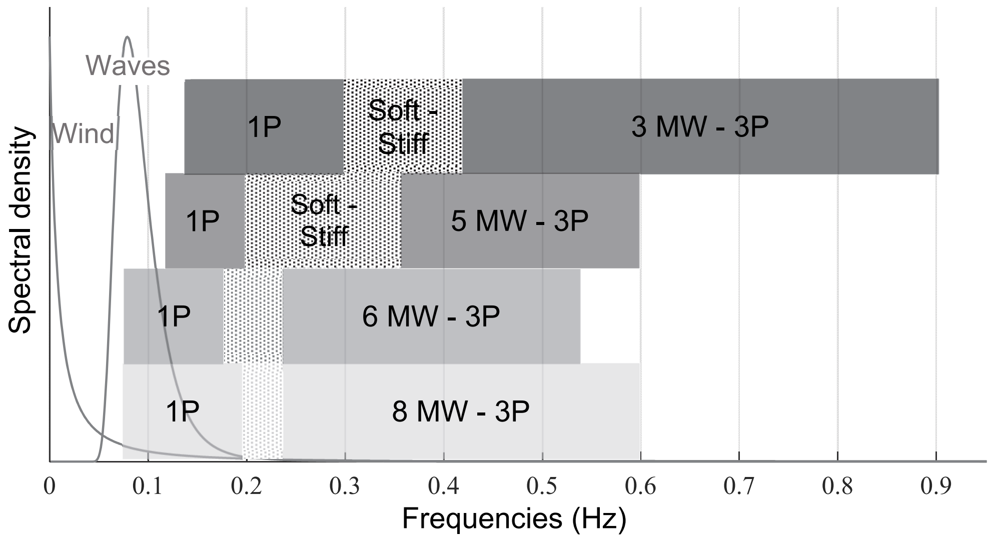
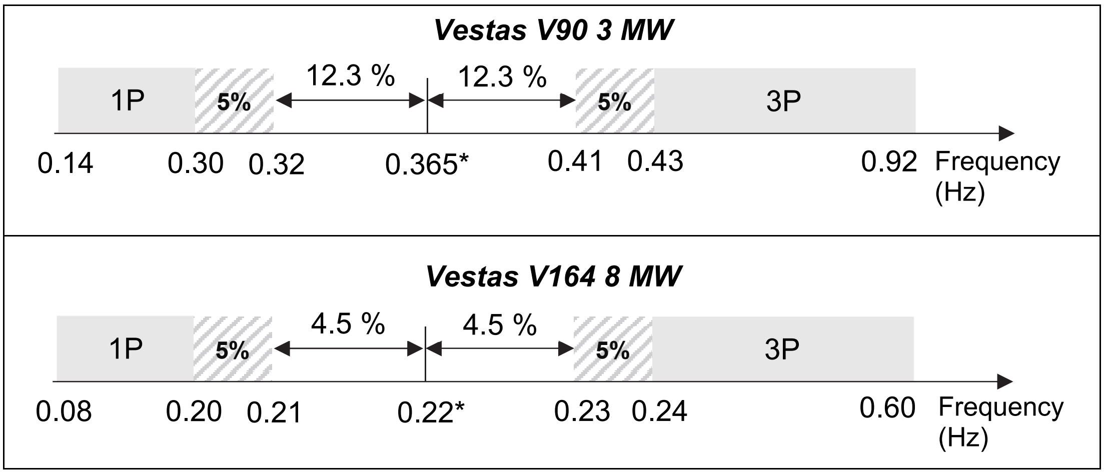


Fig. 2: Excitation frequencies acting on offshore wind turbine Vestas V90 3MW, NREL 5 MW, Siemens 6 MW and Vestas V164 8 MW

The evolution of this natural frequency need to be considered as well. According to LeBlanc et al. (2010a), an offshore wind turbine is submitted to 10^7 loading cycles during a 20 years' utilization period. These great number of cycles influence important parameters such as soil's density, scouring and consequently the soil-structure interaction. According to Kallehave et al. (2015), scouring and sol-pile stiffness are the most important characteristics for the evaluation and evolution of natural frequencies. These loading cycles may also lead to the lateral displacement and the rotation of the structure.

Considering the serviceability limit state (SLS), a safety margin of 5% must be kept between the first natural frequency and the excitation frequencies, according to the DNVGL (2016). As presented in Tab. 1, for a 3 MW turbine, an underestimation or an overestimation of 12.3% in the natural frequency is admissible. For a turbine with a big capacity (8 MW), this permitted interval reduces drastically to 4.5%.

Tab. 1: Excitation frequencies and 5% safety margin for Vestas V90 3 MW and Vestas V164 8 MW



*estimated frequencies

It is, therefore, essential to evaluate the first natural frequency of an offshore wind turbine. This evaluation should be done just after the installation of the turbine. The evolution of this frequency needs to be considered as well.

In this study, various existing methods are introduced for the calculation of the first natural frequency. These methods are based on different modelling of the soil-structure interaction. Based on a 1/60 scaled model of an offshore wind turbine founded on monopile, these methods are compared and discussed. Among the different foundation techniques, the monopile was considered as it corresponds to chosen foundation for 80% of the installed offshore wind turbines.

2 Existing methods for the evaluation of the first natural frequency of an OWT

As underlined in the previous section, the soil-structure interaction is the main factor influencing the behaviour of an offshore wind turbine and its natural frequencies. The standard method based on Winkler model and other existing methods are introduced in this section. These methods are based on various modelling of the monopile and its interaction with the soil as illustrated in Fig. 3.

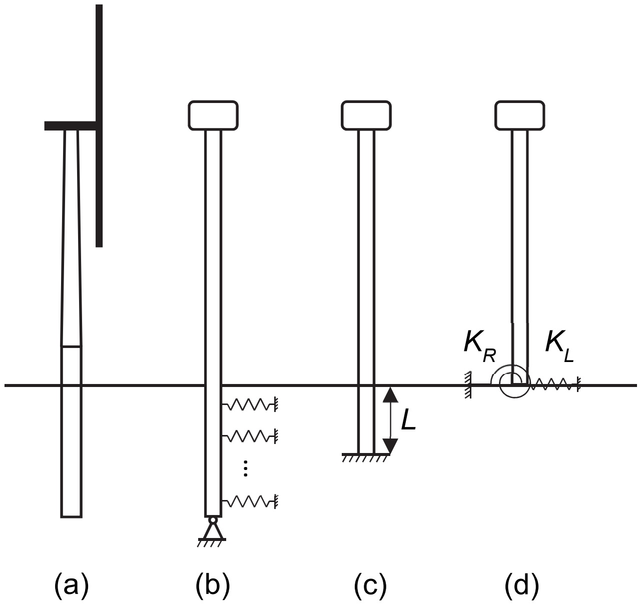


Fig. 3: Standard offshore wind turbine founded on monopile, (b) standard method (Winkler model), (c) equivalent embedded length, (d) elastic end supports

2.1 Standard method and modified standard method

In the standard method detailed in reference guides (API, 2000 and DNVGL, 2016), the turbine is modelled as an Euler Bernoulli beam and the soil-structure interaction is represented by a set of uncoupled lateral springs along the foundation (Winkler model) as shown in Fig. 3 (b). The stiffness of spring depends on the distance between each springs and their initial stiffness E_{py}. This coefficient is evaluated with the *p-y* curves developed by Murchison and O'Neil (1984) for sand and clay. E_{py} is equal to the initial tangent of the *p-y* curves, i.e.:

$$E_{py} = \left(\frac{dp}{dy}\right)_{y=0} = kz \qquad (1)$$

Where k stands for the initial modulus of subgrade reaction (Pa/m) function of friction angle and/or relative density of the soil and, z is the depth.

However, the direct use of the *p-y* curves for offshore wind turbine is questionable as these curves were based on *in situ* tests on two flexible piles with a ratio of length over diameter (*L/D*) equal to 34.4. On the contrary, a monopile has a *L/D* ratio between 4 and 6, which corresponds to an almost rigid behavior. As illustrated in Fig. 4 (a), the behavior of a rigid and a flexible pile, under lateral load, is fundamentally different. The formulation of the *p-y* curve for monopile seem therefore not suitable, particularly as *in situ* measurements reported by Kallehave et al. (2012) show a 5 - 7% relative frequency deviation between the calculated and measured first natural frequency. This result is presented in Fig. 4 (b). The standard method tends to underestimate the soil-structure interaction and consequently underestimate the first natural frequency.

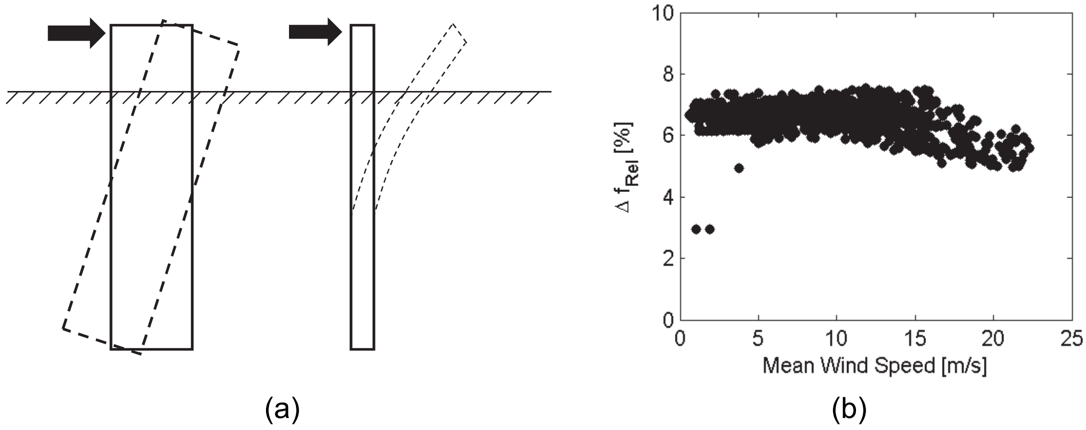


Fig. 4: (a) behavior of a rigid pile (left) and a flexible pile (right) and (b) relative frequency deviations of an offshore wind turbine from Walney park (Kallehave et al., 2012)

To overcome this issue, new formulations for the *p-y* curves were developed taking into account the influence of the diameter of the monopile and the soil's characteristics. Modified *p-y* curves proposed by Kallehave et al. (2012) allowed to get a better estimation of the soil-structure interaction and therefore of the natural frequency of the structure. This formulation was used for the design of wind turbine in the West of Duddon Sands' offshore farm. According to Kallehave et al. (2015), this method increased the wind turbines' lifetime and resulted in a reduction of 6 to 8 % in steel utilized for their construction. Other modified *p-y curves* were also developed regarding various loading cases (see for example Sørensen et al., 2010 for ultimate limit state).

The formulation of the *p-y* curves under cyclic loading is rising similar issues as this definition is based on *in situ* tests conducted on flexible piles submitted to cyclic lateral loads with 100 cycles maximum. An offshore wind turbine is actually subjected to 10^7 cycles. Studies on the evaluation of the soil-structure interaction and the spring's stiffness are strongly needed. So far, the research on offshore wind turbines under cyclic loading is focused mainly on the rotation and lateral displacement of the foundation. Only the studies of LeBlanc et al. (2010a) and Abadie & Byrne (2014) propose an evaluation of the evolution of the soil-pile stiffness.

2.2 Alternative solutions

The easiest existing method consists in substituting the soil and foundation for an embedded pile as illustrated in Fig. 3 (c). According to Kühn et al. (1998), this length, L, is between 3.3D to 3.7D with D, diameter of the pile, for offshore wind turbine founded on monopile.

The last method, presented in Fig. 3 (d), represents the soil-structure interaction with a set of uncoupled springs on the turbine, at the ground level. The wind turbine is modelled by an Euler Bernoulli beam with a point mass on top of the mast. Using this model, Adhikari & Bhattacharya (2012) defined a characteristic equation to calculate the natural frequencies of the turbine. The precise evaluation of the natural frequencies is directly linked to the values of the spring's stiffness. Two analytical methods are introduced to calculate the value of the lateral spring stiffness (noted K_L) and the rotational spring stiffness (noted K_R). The first one arises from Eurocode 8 (Part 5, Annex C, 2004) which defines the expressions for static stiffness of flexible piles embedded in three soil models. A second method defines the stiffness K_L and K_R as function of the soil's shear modulus and Young modulus and also, the pile's Young modulus and moment of inertia.

3 Comparison of the existing methods

The four introduced methods are considered here in order to compare and underline their limits. In this part, the methods are referred as follows:

- *M1*: standard method
- *M2*: method based on Kallehave et al. (2012)
- *M3*: equivalent embedded length method
- *M4*: method based on Adhikari & Bhattacharya (2012)
    - $M4_1$: evaluation of K_L and K_R with Eurocode 8
    - $M4_2$: evaluation of K_L and K_R with the second analytical method

This study is based on the 5 MW offshore wind turbine developed by the NREL (Jonkman et al., 2009) which define all its characteristics. A 1/60 scaled model of the NREL turbine was considered to obtain reference values of the first natural frequency. These results allow to compare the different methods for the evaluation of the first natural frequency.

3.1 Evaluation based on the 1/60 scaled model

The scaled model was made of a mast and a monopile in stainless steel. The model is installed in Fontainebleau sand (NE34). The main characteristics of the scaled model are presented in Fig. 5. As the soil-structure interaction is the main factor influencing the first natural frequency of a wind turbine, a vertical confinement stress σ_V' was imposed on the soil sample. This confinement stress varied from 0 up to 200 kPa in order to modify the soil's stiffness.

Free vibration tests were conducted on the scaled model to evaluate the first natural frequency for various vertical confinement stress. A brief impact force was applied on top of the mast and its resulting vibration was registered with an accelerometer glued on the scaled model. The first natural frequency was evaluated using a method based on wavelet transform. The obtained results are presented in Fig. 6.

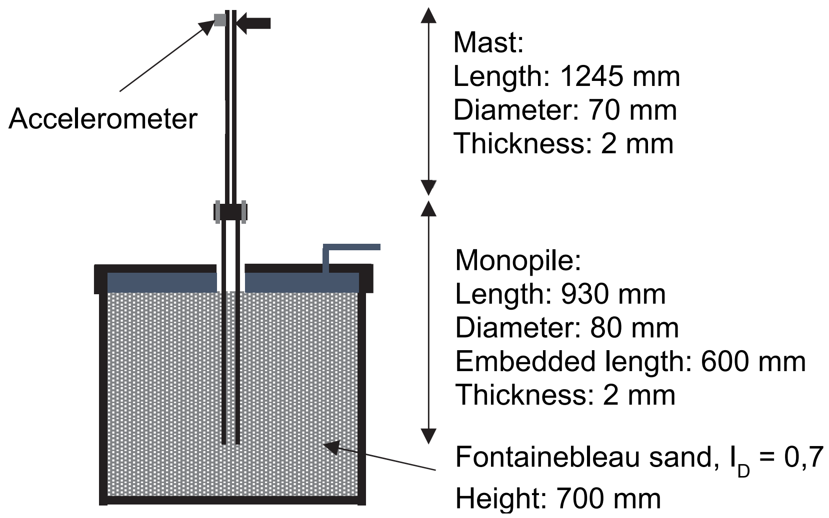


Fig. 5: Sketch of the experimental set-up

Based on the characteristics of the scaled model, the first natural frequency of the structure was evaluated with the four methods described previously. For the *M1* and *M2* methods, the influence of the vertical confinement stress was taken into account in the calculation considering the variation of depth in the evaluation of the initial stiffness of the springs E_{py}. The equivalent embedded length method doesn't allow to include the impact of σ'_V, the calculation was therefore done for an embedded length equal to *3.3D* and *3.7D*. For the method *M4*, the variation of the vertical confinement stress was considered with the evolution of the soil's Young modulus and shear modulus. The results obtained for these four methods are presented in Fig. 6.

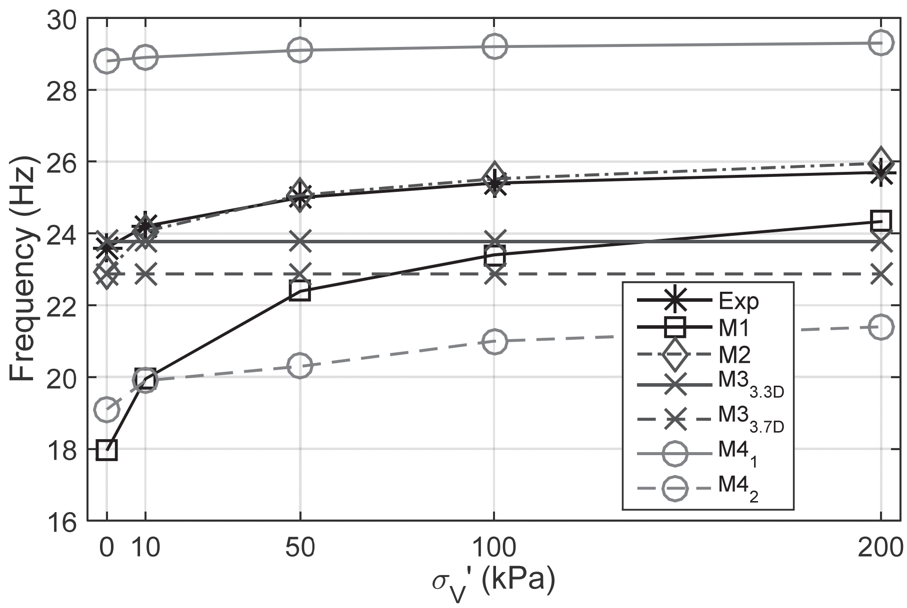


Fig. 6: Evolution of the first natural frequency with soil confinement stress

3.2 Discussion

As it was underlined previously, the standard method underestimates the soil-structure. In fact, the first natural frequency was underestimated with an average error of 13%. The modified standard method, developed by Kallehave et al. (2012), gives the best evaluation with an average error of 0.4%. The method *M3* allows a quick and easy a first evaluation of the natural frequency with an average error between 1% (for $L = 3.3D$) and 3% (for $L = 3.7D$). Finally, the method *M4* gives the highest overestimation (17%) based on Eurocode 8 and the highest underestimation (18%) for the Adhikari & Bhattacharya (2012) analytical method.

The equivalent embedded length method seems to be an appropriate method to obtain a satisfactory first evaluation. The modified standard method *M2* is the most suitable method for a monopile with a rigid behaviour. The method developed by Adhikari & Bhattacharya (2012) needs a fine evaluation of the springs' stiffness which represent the main factor is the calculation of the first natural frequency.

4 Conclusion

This study is an introduction around the dynamic of offshore wind turbine and its challenges. It was mostly focused on the evaluation of its natural frequency just after its installation when no cyclic loading has occurred yet. In this study, four methods for the evaluation of the first natural frequency of an offshore wind turbine were introduced and compared based on a 1/60 scaled model of the NREL 5 MW wind turbine founded on monopile.

The equivalent embedded length method allows to obtain a satisfactory first result before initiating any complex calculation. A fine evaluation can be obtained with the method developed by Kallehave et al. (2012). These results are in agreement with Kallehave et al. (2015): taking into account the diameter and soil's characteristics in the formulation of the *p-y* curves allow to significantly enhance the evaluation of the soil-structure interaction and the first natural frequency.

A detailed study and methods are still necessary in order to apprehend the evolution of the dynamic of the wind turbine while submitted to various cyclic loading.

5 Literature

Abadie, C. & Byrne, B. (2014)
Cyclic loading response of monopile foundations in cohesionless soils, Proceedings of the 8th International Conference of Physical Modelling in Geotechnics, 779 – 784.

Adhikari, S. & Bhattacharya, S. (2012)
Dynamic analysis of wind turbine towers on flexible foundations, Shock and Vibrations, Vol. 1, n°11, 37 – 56.

API (2000)
American Petroleum Institute Recommended Practice 2A – WSD, Planning, Designing and Constructing Fixed Offshore Platforms – Working Stress Design.

DNVGL (2016)
DNVGL-ST-0126, Offshore Standard: Support structures for wind turbines.

EN 1998-5 (2004)
Eurocode 8: Design of structures for earthquake resistance – Part 5: Foundations, retaining structures and geotechnical aspects.

Jonkman, J., Butterfield, S., Musial, W. & Scott, G. (2009)
Definition of a 5-MW reference wind turbine for offshore system development, National Renewable Energy Laboratory NREL/TP-500-38060.

Kallehave, D., LeBlanc, C. & Liingaard, M. (2012)
Modification of the API p-y formulation of initial stiffness of sand, Offshore site investigation and gotechnics: integrated technologies – present and future, 465 – 472.

Kallehave, D., Byrne, B., LeBlanc, C. & Mikkelen, K. (2015)
Optimization of monopoles for offshore wind turbines, Philosophical Transactions of the Royal Society A, Vol. 373.

Kühn, M., Van Bussel, G.J.W., Schontag, C., Cockerill, T.T., Harrison, R., Harland, L.A. & Vugts, J.H. (1998)
Methods assisting the design of offshore wind energy conversion systems, Opti OWECS final report, Vol. 2, Delft: Institute for Wind Energy.

LeBlanc, C., Houlsby, G. & Byrne, B. (2010a)
Response of stiff piles to long-term cyclic loading, Géotechnique, Vol.60, n°12, 79 – 90.

Murchison, J. & O'Neil, M. (1984)
Evaluation of p-y relationships in cohesionless soils, Analysis and Design of Pile Foundations, Proceedings of a Symposium in conjunction with the ASCE National Convention, 174 – 191.

Sørensen, S., Ibsen, L. & Augustesen, A. (2010)
Effects of diameter on initial stiffness of p-y curves for large-diameter piles in sand, Numerical Methods in Geotechnical Engineering, 907 – 912.

WindEurope. (2017)
The European offshore wind industry, Key trends and statistics 2016, WindEurope.