ON THE IMPLICATIONS OF ADVANCED MONOPILE DESIGN METHODOLOGIES IN OFFSHORE WIND TURBINES

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Abstract

The design of Offshore Wind Turbines (OWT) is a complex process involving several stages: wind turbine selection, tower and sub-structure design, as well as foundation design and installation. A successful design requires close interaction between these components in order to satisfy the main design requirements, namely the capacity and accumulated rotation for the foundation and dynamic response and fatigue for the whole system. Recent research has revealed that the current design methods for laterally loaded piles, when applied to short and stubby OWT monopiles, underestimate their initial stiffness and capacity. Advanced Finite Element (FE) analysis, with realistic modelling of the ground conditions can accurately reproduce soil response around a monopile, and hence improve the design, ultimately leading to cost reduction of monopile foundations. In the present paper, the impact of economies in foundation design on the overall design of a realistic OWT is explored. The NREL 5 MW baseline wind turbine is modelled through FE analysis under several characteristic design load cases. The advantages of using FE analysis when compared to traditional methods, in particular with respect to capacity and dynamic response, are demonstrated and discussed.

1. Introduction

Economy in installation and foundation design plays a major role in the development of offshore wind energy. Contrary to oil and gas platforms, offshore wind farms require the installation of a very large number of pile foundations. Therefore, optimisation of these foundations may represent a significant saving. As a result, accurate models capable of realistically reproducing the integrated system, including the soil behaviour, are fundamental for the economy and viability of such projects.

Offshore Wind Turbine (OWT) design involves a number of stages, including wind turbine selection, tower, sub-structure design, as well as foundation design and installation (see Arany et al (2017) for additional details). Once a preliminary geometry of the pile is obtained, and more data of the site collected, further advanced analyses are required for optimisation, typically involving finite element (FE) analysis.

Previous studies exist investigating the effect of soil-structure interaction and considering wind turbine aerodynamics, either using the standard p-y approach (Bush & Manuel, 2009; Jonkman & Musial, 2010) or extracting a coupled-spring model from preliminary FE analysis (Jung et al, 2015). The present study aims to compare traditional design methods with advanced soil FE modelling, while considering wind turbine aerodynamics using a distributed springs modelling strategy.

2. Scope of the study

Recent large scale tests on laterally loaded piles at Cowden (Byrne et al, 2015) have demonstrated the advantages of employing FE analyses to simulate the behaviour of large diameter monopiles in overconsolidated clays (Zdravković et al, 2015). Along with the outcome of these large scale tests, design guidelines (DNV-GL, 2016) have suggested that for large diameter monopile design, FE analysis should be employed. This study focuses on the advantages of using FE methods over current traditional methods.

It has been shown that the use of FE analysis leads to more economical designs of pile foundations when compared to the traditional p-y methods. The objective of the study is to illustrate the challenges and the

pitfalls of traditional methods when applied to the design of offshore wind turbine monopiles. To ensure the chosen example is realistic, the main design constraints and realistic sources of information are used, including site conditions, soil characterisation, wind turbine characteristics and industry basis for design.

The final objective is to describe a methodology for setting-up integrated models capable of representing the whole wind turbine system. The derived model can then be used for future fatigue assessment and quantification of the response of the wind turbine under varying environmental and operational conditions. Resulting models are able to reproduce accurately the following aspects of the system: the servo-control of the wind turbine, the dynamic response of the super-structure, hydrodynamic loading and soil-structure interaction.

3. Methodology

The principal tools employed in this study are the FE software ICFEP for soil-structure interaction (Potts & Zdravkovic, 1999) and the software F.A.S.T. (Jonkman & Buhl, 2005), for wind turbine modelling, (version FAST v7.02.00d-bjj).

The set-up of the coupled wind turbine model, referred in the following as the aero-elastic model, uses the same methodology and input structure as the OC3 phase II distributed spring model (Jonkman & Musial, 2010). A distributed spring approach is recommended over a coupled spring approach by the developers of F.A.S.T, as the coupled spring model approach may not capture properly the second modes and may introduce erroneous loads and stability predictions (Bir & Jonkman, 2008). Conversely, the soil-structure interaction is simulated using a 3D FE model of the soil, foundation and superstructure. The set-up of the FE model and mesh details follow the methodology described in (Zdravković et al, 2015).

3.1 Idealisation of soil conditions

The water depth considered for the design exercise is 20 metres and the ground conditions are assumed to be representative of the North Sea overconsolidated clays. The soil profile corresponds to an idealisation of the ground conditions at Cowden, NE England (Powell & Butcher, 2003), consisting of a single layer of Cowden till, described in Figure 1. The initial stress profile was obtained using a bulk unit weight (γ) of 21.19 KN/m^3 , hydrostatic pore pressures and a coefficient of earth pressure at rest varying with depth (Figure 1d). The undrained strength profile in triaxial compression increases linearly with depth, starting at 100 kPa at ground level, with a gradient of 2.86 kPa per metre (Figure 1b) and is consistent with the prescribed K0 and OCR profiles (Figure 1d and Figure 1a).

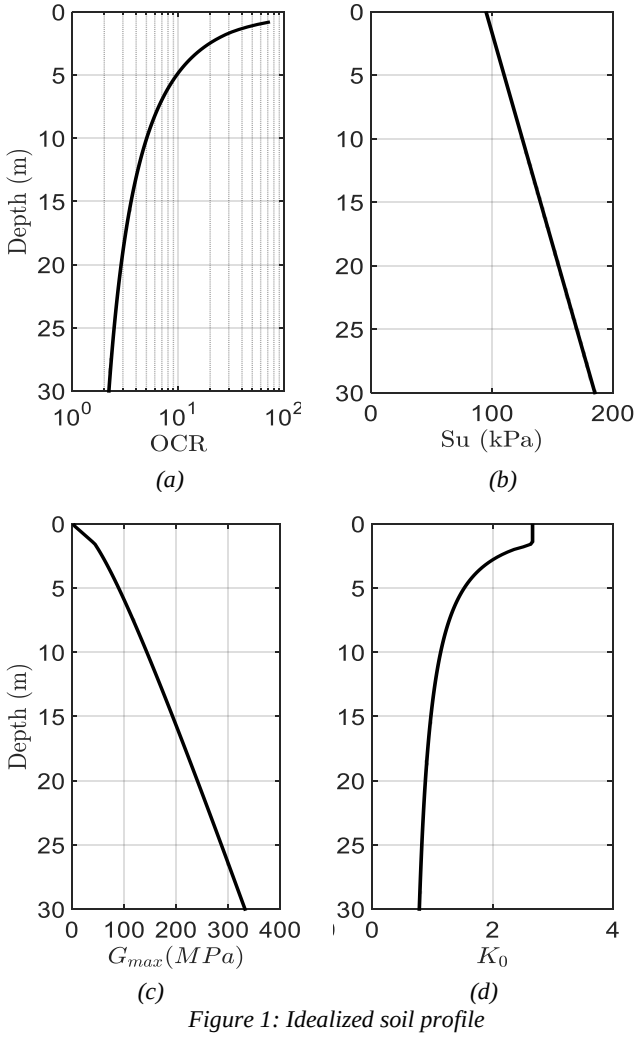


Figure 1: Idealized soil profile

The model used is an expanded generalisation of the modified Cam clay (MCC) model (Roscoe & Burland, 1968), utilising a Hvorslev surface on the dry side (Tsiampousi et al, 2013), the general expression of Van Eekelen (1980) for the yield and plastic potential surfaces in the deviatoric plane and a non-linear stiffness variation with strain, as described in Taborda et al (2016). The model parameters are as those reported in (Zdravković et al, 2015).

3.2 Reference wind turbine and superstructure

The wind turbine used for the study is the Baseline 5MW wind turbine of NREL (Jonkman et al, 2009). This turbine is generally used for benchmark analysis and shares characteristics with the commercial Re-Power 5 MW wind turbine. The superstructure (sub-structure, tower and rotor nacelle assembly) used in this study corresponds to that included in phase I of the OC3 validation project (Jonkman & Musial, 2010).

During the mesh preparation process, the performance of the structural shell elements in ICFEP 3D FE model was checked by carrying out static and dynamic simulations and comparing the results with those reported by Damiani et al (2013). ICFEP 3D model shows good agreement with the validated original model, as shown in Table 1.

Table 1: Structural validation, deflection at RNA level and first natural frequency,

	Tip displacement (m)	
Horizontal load	**ICFEP (3D shell)**	**SubDyn* (1D beam)**
2000 kN	1.624	1.645
3500 kN	2.841	2.878
1st frequency	0.277	0.280

*(Damiani et al, 2013)

3.3 Design requirements

The design requirements were obtained from a public tender for design of the Krieger's Flak wind farm (Bülow & Gravesen, 2008). Not every condition is considered in this paper due to space limitations. Those that have been used are summarised in Table 2:

Table 2: Design requirements for 20m water depth

	H (MN)	M (MNm)
Extreme loads at mudline	4.4	236.0
Operational loads at mudline	3.5	154.0
Max. rotation at mudline	0.25°	
First natural frequency	$0.26 \geq f_N \geq 0.23$ Hz	

3.3 FEA modelling and extraction of reactions

Three loading stages are considered, simulating the pseudo-static loads described in Table 2: operational load and extreme load, while the third stage consisted of a displacement-controlled loading to failure.

Once the load-displacement response and lateral capacity of the pile foundation were evaluated, further dynamic simulations were carried out to assess the validity of the resulting mode shapes for the future aero-elastic model. These dynamic simulations consisted of short-time perturbations of the first mode of the system within the range of the operational load. Finally, in order to include the soil-structure interaction in F.A.S.T. the nodal forces acting on the shells were used to extract the reactions acting on the pile.

3.4 Aero-elastic Modelling

The software F.A.S.T. (Jonkman & Buhl, 2005) was recompiled with authors' user-defined subroutines accounting for the soil-structure interaction. The algorithm for controlling the blade-pitch system, the generator and the gearbox is the standard power control algorithm distributed with the 5MW baseline wind turbine (DISCON.dll). The software and source code is freely available at the NREL webpage. Once the aero-elastic models were set-up, six 600 seconds transient simulations were performed under power production conditions, with severe sea state (DLC1.6) as described in DNV-GL (2016). This design load case typically leads to the maximum loads acting at mudline level.

Wind fields with average speeds from 8 to 18 m/s were generated, while the sea state was generated using a JONSWAP spectra with reference wave height (H_s) of 5.6 metres and a period of 12.1 s. The considered drag and inertia hydrodynamic coefficients are C_D = 1.15 and C_A = 1.75 for all simulation batches. An example of the environmental conditions generated is shown in Figure 2.

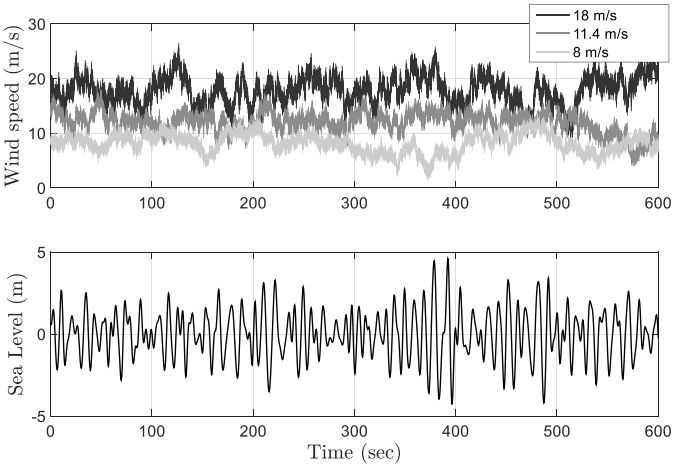


Figure 2: Mean, maximum and minimum environmental conditions for aero-elastic simulations

4. Results

4.1 Resulting pile dimensions

The reference diameter considered for design is 6 m, equal to the diameter of the sub-structure base. Different pile lengths are obtained depending on the method used to simulate soil-structure interaction: standard p-y curves or the FE analyses. A summary of the design requirements listed in Table 2 which are fulfilled by each geometry is shown in Table 3.

Table 3: Design requirements fulfilled

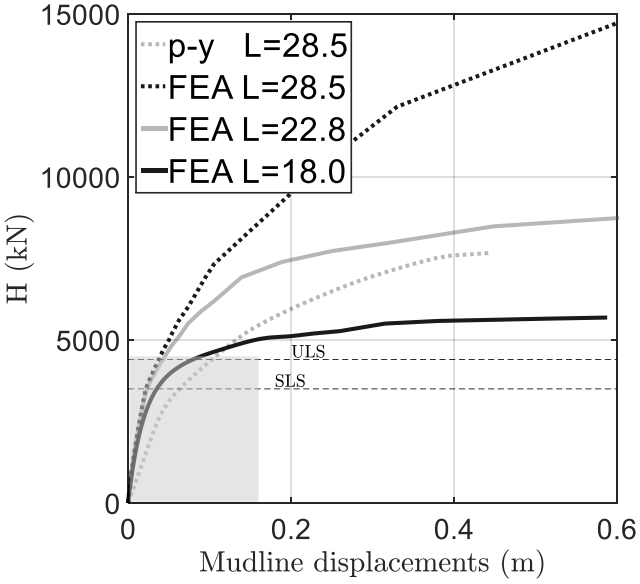
	L = 28.5 m	L = 22.8 m	L = 18.0 m
FE (ULS)	YES	YES	YES
p-y (ULS)	YES	YES	NO
FE (SLS)	YES	YES	YES
p-y (SLS)	YES	NO	NO
Eigen FE (SLS)	YES	YES	YES
Eigen p-y (SLS)	YES	YES	YES

The standard p-y soil reaction curves rely on parameter ε_{50}, which denotes the strain level at half the maximum deviatoric stress observed in undrained triaxial compression tests of undisturbed soil samples (DNV-GL, 2016; API, 2010). In order to ensure compatibility between the two different approaches used in this paper – FE method and standard p-y curves – the values of ε_{50} were obtained directly from numerical simulations of undrained triaxial tests. The values of ε_{50} considered for this study are detailed in Figure 4.

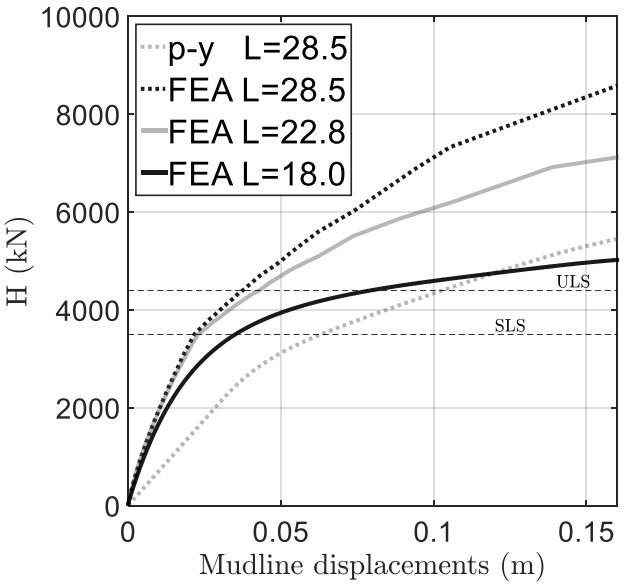
Three pile lengths of 28.5, 22.5 and 18.0 m were obtained for the design requirements listed in Table 2, giving a slenderness ratio of 4.75, 3.8 and 3.0, respectively. The most restrictive design condition of this particular example was found to be the rotation requirement at the mudline. Recent studies have demonstrated that the use of the current p-y methodology for clay often leads to the underestimation of the initial stiffness of the pile-soil system (Byrne et al, 2015). As a result, in the present case, the monopile had to be extended to 28.5 m when using the standard p-y curves in order to meet the design requirement in terms of maximum rotation at mudline. The second most restrictive criteria was lateral capacity, with a required embedment of 22.8 m when using the standard p-y curves. Finally, the third geometry was determined as the length at which the design extreme load would be around 80% of the estimated capacity from the FE analysis, yielding a final embedment depth of 18.0 m.

4.2 Pseudo-static tests using FE

In order to establish a fair comparison between the current p-y methodology and the FE method, the static version of the standard p-y curves was used for the 28.5 m pile. The load-displacement curves at mudline for the considered cases with the operational and extreme load cases in Table 2 are shown in Figure 3. The comparison confirms that for the proposed conditions the standard p-y curves tend to underestimate both the stiffness and the lateral capacity of the pile when compared to FE predictions.



(a)



(b)

Figure 3: Load-displacement curves at mudline (a) large displacement, (b) initial response

In the case of the deflected shape, contrary to the response obtained in the p-y analysis, the FE analysis of the 28.5 m long pile shows that in the operational range the pile still behaves in a flexible manner despite its low slenderness ratio (L/D < 5), see Figure 4. This type of behaviour is also visible in the second considered geometry (22.8 m). Such deflected shape is typical of cases where the operational load is far from the capacity of the pile, meaning that only the upper part of the soil is mobilized and no significant toe-kick reaction will appear. As a consequence, when considering loads within the operational range, standard p-y curves predict an earlier pile-toe kick-back, a deflected shape closer to a rigid body rotation, and also a rotation point located at higher depths.

Conversely, a more rigid body behaviour is exhibited in the geometry with an embedment of 18 m. In this

case the operational load lies closer to the ultimate capacity of the pile than any of the three cases.

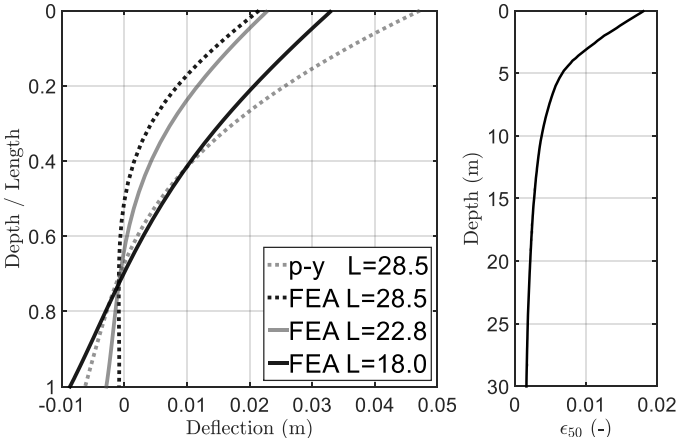


Figure 4: Deflected shape at operational load and ε_{50} profile considered for the standard p-y curves

In summary, the analyses show that flexible behaviour can be observed even for low L/D ratios if the foundation is subjected to low operational load - lateral capacity ratios. Under such loading conditions, the influence of the soil's small strain stiffness is considerable, suggesting that its accurate modelling is required, regardless of the slenderness ratio of the pile. Indeed, disregarding this aspect of soil behaviour may introduce substantial errors in the modelling of offshore wind turbines, especially when estimating the fatigue and the design life of its structural members.

4.3 Dynamic response and mode shapes

In order to compute the structural response, F.A.S.T. (Jonkman & Buhl, 2005) requires the appropriate mode shapes of the tower substructure and pile system, together with the applied external loads (Bir & Jonkman, 2008), to be specified. The displacement field provided by F.A.S.T. corresponds to a linear combination of these modes. Therefore, if the code is used in very non-linear problems, great inaccuracies may occur meaning appropriate preliminary analyses to assess the validity of the mode shapes are necessary.

In the present case, this was carried out using transient ICFEP 3D FE analyses, as described in section 3.3. It was found for all cases that, within the operational range, the displacement field calculated using the FE method could be captured with the two first modes in each of the directions: fore-aft (FA) and side to side (SS). Subsequently, the first mode frequency was calculated for each of the considered pile geometries, using both the standard p-y approach and the FE reactions. Results of the mode shapes and natural frequencies further confirm that the use of the p-y curves underestimates the stiffness of the foundation soil, leading to smaller frequencies for the first and second modes than when using the FE reactions.

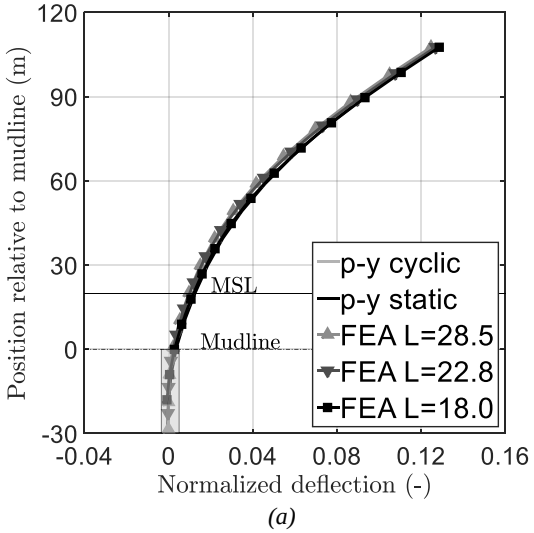
Therefore, when using a p-y approach, it is advisable to design the monopile towards the lower bound of the limiting frequency range, as it is very likely that the overall stiffness of the system may be underestimated. However, it should be noted that large differences in soil stiffness do not have a great influence on the magnitude of the first natural frequency. In effect, the rotor-nacelle assembly mass and the length of the tower play a more significant role in satisfying the first natural frequency serviceability limit, than the soil-structure interaction.

Table 4: First and second FA and SS natural frequencies

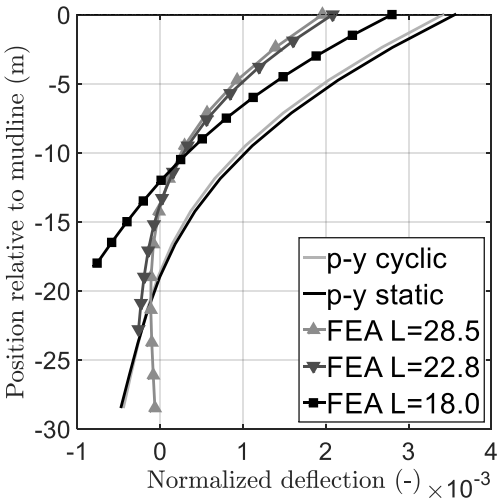
	Support natural frequencies (Hz)			
	1st FA	**1st SS**	**2nd FA**	**2nd SS**
p-y cyclic	0.232	0.231	1.39	1.25
p-y static	0.231	0.23	1.38	1.25
FEA L = 28.5	0.244	0.242	1.50	1.35
FEA L = 22.8	0.241	0.240	1.49	1.35
FEA L = 18.0	0.235	0.234	1.42	1.27

In Figure 5 and 6 the resulting first and second mode shapes for each of the pile geometries and soil-interaction considered are shown. The obtained mode shapes reinforce the earlier discussion shown in Figures 3 and 4 on the flexible-rigid behaviour.

Only small differences are found between the standard cyclic and the static p-y curves within the operational range (see enlarged details below mudline of Figures 5b and 6b), suggesting that the post-peak behaviour of the cyclic p-y curves is not triggered for most of the pile. Therefore, it can be concluded that the inability to capture the real stiffness arises from the underestimation of stiffness of standard p-y curves.

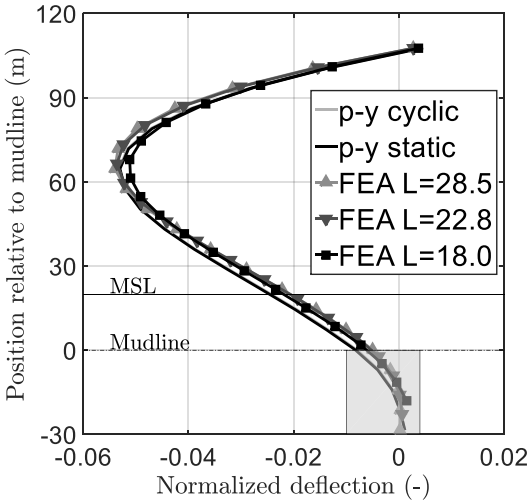


(a)

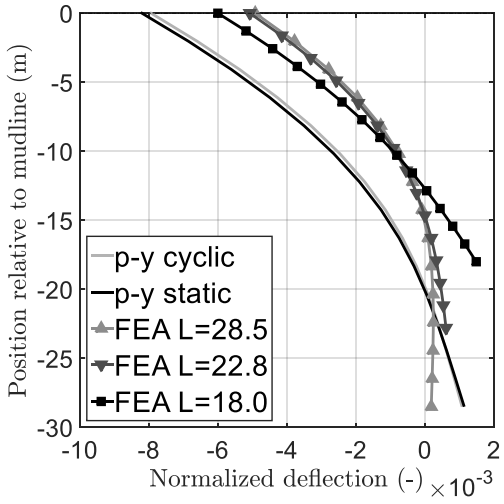


(b)

Figure 5: Fore-aft first modes: Tower-Substructure-Foundation (a), below mudline detail (b)



(a)

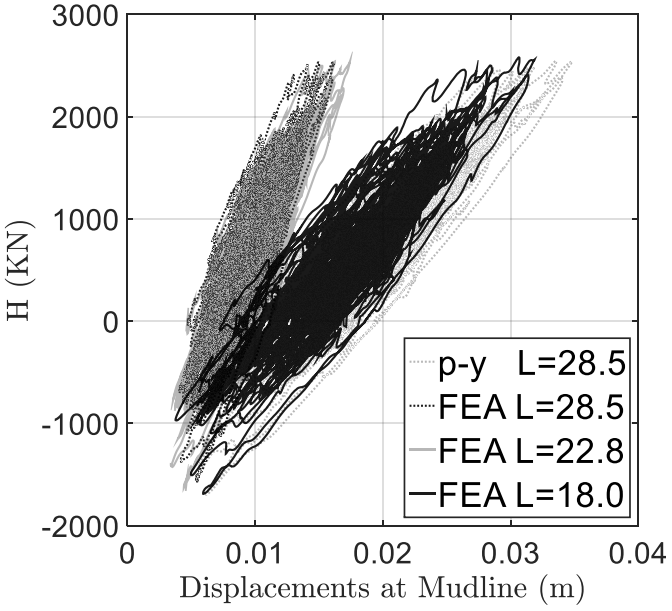


(b)

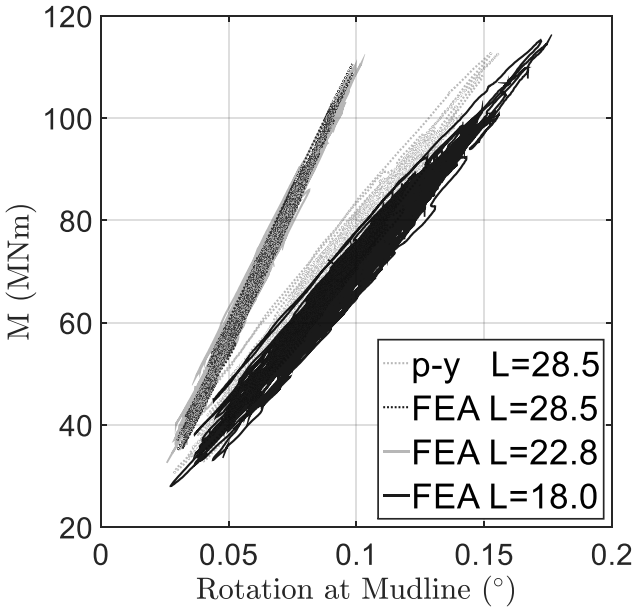
Figure 6: Fore-aft second modes: Tower-Substructure- Foundation (a), below mudline detail (b)

4.4 Time domain aero-elastic simulations

A total of 24 aero-elastic 600 s transient simulations, 6 for the four cases (p-y: 28.5 m, FE: 28.5 m, 22.8 m, 18.0 m) were carried out. The maximum load acting at the mudline corresponds to the rated wind speed (11.4 m/s). For the small batch of transient analyses the maximum load registered in absolute value is lower than its equivalent pseudo-static operational load, however its amplitude lies within the range of the operational load. This is a consequence of the fact that hydrodynamic loads obtained through Morrison formula (DNV-GL, 2016) tend to have an average value of zero. Conversely, aerodynamic loads have non-centred mean values and smaller amplitudes. Figure 7 shows the force–displacement and moment–rotation curves for power production at rated wind speed for the four aero-elastic obtained models.



(a)



(b)

Figure 7: Force-displacement curves at the mudline for rated wind speed (11.4 m/s) and severe sea state

The results of the batch of simulations show that the 18 m long pile simulated using the FE method to estimate the soil-structure interaction behaves in a similar manner to the 28.5 m long pile whose soil-structure response has been estimated with standard p-y curves. To compare the performance of each model,

the response of the system at three locations is investigated: the mudline, the tower top and the root of the blades.
Probability density functions are extracted for the time series at each of the control points. Figure 8 shows an example of this type of analysis for the 18 m long pile. Probability distribution functions of each individual simulation and its aggregate probability distribution over the whole batch of simulations is shown.

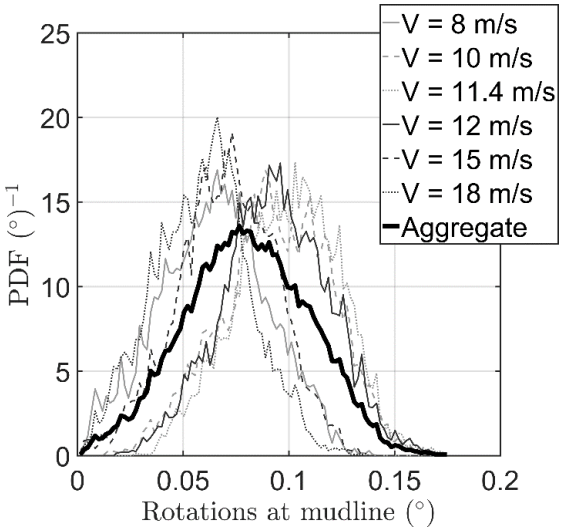


Figure 8: Discrete and aggregate probability density function of rotation at mudline (DLC1.6)

Comparison of the aggregate probability distributions of displacement at mudline level and acceleration at the top of the tower outline the two possible pitfalls that may occur during monopile design for offshore wind turbines: the underestimation of stiffness and the wrong mode of deflection in operational conditions.

Firstly, the response of the 18 m long pile is similar to the pile with an embedment of 28.5 m if the standard p-y curves are used (Figure 9). Secondly, it can be seen how increasing the embedment from 22.8 m to 28.5 m does not result in an improvement in the response, due to the fact that the mode of deflection is flexible in both cases.

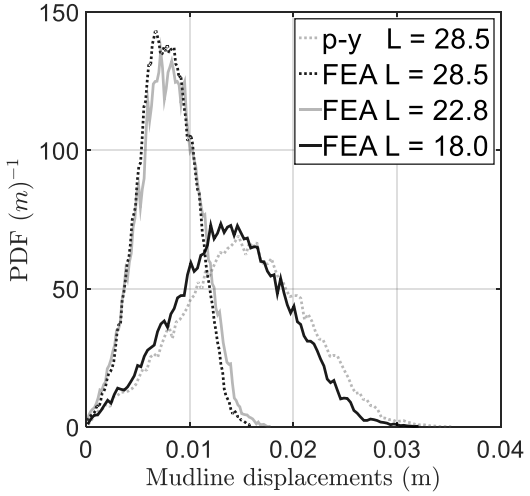


Figure 9: Aggregate probability density distribution of displacement at mudline

While the soil-structure interaction does not play a significant role in the maximum deflection at the tower top, it has a more significant impact on the acceleration at this location and therefore on the fatigue and design life of the tower. Figure 10 shows the cumulative probability distribution function of the acceleration at the tower top. Higher acceleration values are predicted if the current p-y curves are employed instead of the FE approach.

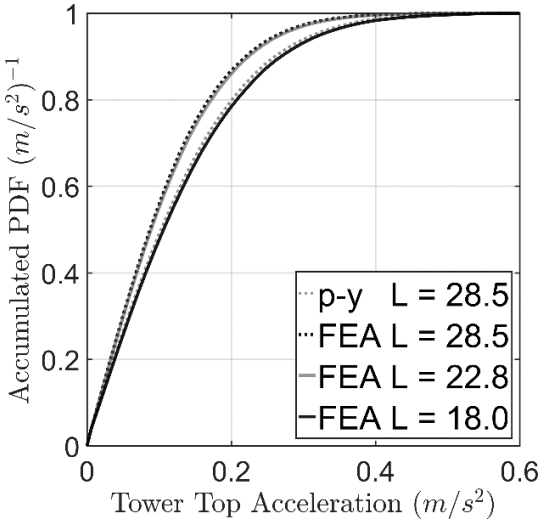


Figure 10: Accumulated aggregate probability density distribution of accelerations magnitudes at tower top.

Finally, at the last control point – the root of the blades – it has been found that the methodology used to simulate the behaviour of the foundation soil does not have a direct influence on the loads acting on the blades. Results show that the servo-control system of the turbine is capable of damping the effect of the vibration induced by soil-structure interaction, with no significant impact on the fatigue and design life of the blades.

5. Conclusions

The paper presents a realistic design scenario for large diameter monopiles used as foundations for offshore wind turbines. The methodology for setting up the aero-elastic model has been described and two approaches have been used to simulate soil-structure interaction: the standard p-y curves (API, 2010; DNV-GL, 2016) and advanced FE analyses.

Results show the advantage in terms of economy of FE methods over standard p-y curves. The major pitfalls in the use of simple p-y methodologies for offshore wind turbine design are outlined: the underestimation of the initial stiffness and the inability to predict the shape of the mode of deflection in the range of the operational load. The combination of these two factors tend to yield conservative designs.

The effect of the soil-structure interaction has been quantified for three different geometries. Results of

the simulations show that soil-structure interaction has little influence on the blades but a significant impact on the tower. Conversely, soil-structure interaction plays an important role in the fatigue of the tower, influencing the accelerations and mode of vibration of the system.

Additionally, the paper describes a methodology to include advanced finite element analyses in engineering practice, which can be used to further optimise the design of foundations for offshore wind turbines. In this example more emphasis has been placed on the methodological aspects of integrating FE analyses rather than advanced modelling aspects. Aspects such as installation effects, cyclic creep and cyclic stiffness degradation have not been considered. The use of F.A.S.T. is valid as long as the deflected shape of the pile can be captured by the mode shapes, in this sense it is important to carry out transient FE analysis to verify that the modal superposition assumption remains valid.

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