

Pile Apparent Fixity Length Estimation for the Jacket-type Offshore Wind Turbines under Lateral Loads Applicable to Fatigue Analysis

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ABSTRACT

Modelling the soil-pile interaction using the Finite Element Method (FEM) might be a time-consuming process and required entirely specific soil properties. Moreover, most of the codes that have been developed for offshore wind turbines use one or more of some simplified linear foundation models suitable for dynamic analysis such as Apparent Fixity (AF) model. In the AF model for pile foundation systems, a fixity length level below the seabed is designated for the pile. It is assumed that the whole structure, including the pile and support structure, is cantilevered at the corresponding fixity length level without surrounding soil while has identical behavior to a pile penetrated the real soil. In this study, the apparent fixity length of the piles sustaining the OC4 offshore wind turbine on the seabed is estimated using a nonlinear soil-pile interaction analysis following a dynamic response analysis of the structure under lateral loads during turbine power production. Given the stiffness coefficients of the pile heads, different apparent fixity lengths are obtained, and the minimum one, verified by modal analysis, is also determined, which can be presumed in fatigue analysis. It is also demonstrated that the estimated minimum fixity length has a smaller value than the piles' critical length.

1. Introduction

Finding new energy resources, especially clean and renewable ones, have always been among the human's main concerns since the late 20th century. Wind energy is a sort of renewable and clean resources and is used to generate electrical power by application of wind turbines. Wind turbines, in terms of place of operation, are classified into onshore and offshore wind turbines (OWT). A wind farm is set up when several OWTs are placed at a specified location together. Since the earliest offshore wind farm was installed in Denmark in the 1990s, the development of this technology to achieve more reliable electrical power with reasonable cost has been the main purpose of experts involving in the offshore industry [1]. OWTs have various types of foundation systems and are designed considering different water depths, environmental conditions, and seabed soil properties. They are generally distinguished by their foundation systems, namely fixed and floating types. Monopile, jacket, tripod, and gravity-based foundations are fixed OWT and semi-sub, TLP, and spar foundation systems are those used as floating. Investigation of soil-pile interaction for fixed OWT is a complicated task and required nonlinear analyses. In order to assure the results are highly accurate, the Finite

Element Method (FEM) is extensively used to examine soil-pile interaction using soil properties such as p-y curves. These curves are yielded from in-situ experiments, whereas some simplified methods approximately lead to reasonable outcomes concerning soil-pile interaction. In this regard, Bush and Manuel [2] investigated the effects of applying four different monopile foundation models for offshore wind turbines, including Fixed-Base (FB) and Flexible in shallow waters subjected to extreme loads with return periods of 20 years. Flexible models include the apparent fixity (AF) model, the Coupled Springs (CS) model, and the Distributed Springs (DS) model. In the FB model in which the structure connected rigidly to the seabed, the soil profile is not taken into account. In the AF model, the pile is assumed as a cantilever beam continued downward the seabed and fixed at a specific level where the pile has identical behaviour to the case in which it is embedded into the real soil profile. In the CS model, coupled rotational and translational springs on pile tip – seabed level – demonstrate the soil behaviour. In the DS model, linear elastic springs are placed along the pile and represent soil layers' stiffness values. These models are based on a study by Jonkman et al. [3] through which some simplified linear

foundation models derived by the Endowed Chair of Wind Energy (SWE) at the University of Stuttgart in Germany, appropriate to use in a dynamic analysis, have been presented. The use of the AF model is always accompanied by a challenging issue, to what length the pile has to be fixed below the seabed level. According to Barltrop and Adams [4], rough approximations to the apparent fixity lengths are $3.5D$ - $4.5D$ for stiff clays, $7D$ - $8.5D$ for very soft silts, and $6D$ in the general analyses where D is the pile diameter. This may, however, vary owing to different soil properties. Furthermore, given that each location has its particular sea states and environmental load conditions, it seems more rational to estimate an adequate specific apparent fixity length for each case. Akdag [5] performed an investigation of an alternative pile foundation for jacket OWT in Mustang Island with closely spaced double piles at the edge of the jacket, which led to a reduction in piles embedment length up to 50 %. Wei Shi et al. [6] investigated the effect of the soil-structure interaction on the response of an offshore wind turbine with a jacket-type foundation. They considered two different models of flexible foundation - the p-y model and the p-y model considering pile groups effect - to compare the dynamic responses with the fixed-base model. Moreover, they showed that influence of the soil-structure interaction on the response of the jacket foundation predicts that the flexible foundation model is necessary to estimate loads of the offshore wind turbine structure accurately. Khodair and Abdel-Mohti [7] studied soil-pile interaction for a composite pile using FEM and Finite Difference (FD) method. They used *Abaqus* and *SAP2000* for FEM and *LPILE* for the FD method. They found, finally, a close correlation between the results obtained by the FEM and the FD solution. Furthermore, the effect of applying an axial load to the pile on the produced bending moment and lateral displacement along the depth was minimal and negligible. The effect of the seabed slope on the piles' behaviour of a fixed offshore platform under lateral loads was investigated by Muthukkumaran and Arun [8]. Their results indicated that the lateral displacement at the pile tip, the seabed level, increases with the seabed slope. In the present study, initially, an aero-hydro-servo-elastic simulation of the OC4 offshore wind turbine [9] supported by a FB jacket is carried out using FAST [10]. Operational load conditions considering the fatigue analysis, which is the further concern of this study, are used to obtain the time history of shear forces and flexural moments at the sea bed level -leg bottoms. Subsequently, nonlinear soil-pile interaction analyses under lateral excitations are conducted using *LPILE* [11], which leads to piles lateral deflections given that penetration depth and the pile heads stiffness matrices. Ultimately, the apparent fixity lengths for the piles are estimated using Euler-Bernoulli beam theory and the minimum applicable fixity length verified by modal analysis is chosen.

2. Modelling Considerations

The reference jacket "UPWIND" described by Vorpahl and Popko [12] supporting a 5MW baseline wind turbine [13], developed at the National Renewable Energy Laboratory (NREL) of the United States, is considered here as a case study. It has a hub with a diameter of 3 meters located 90.55 meters upward from the mean sea level. Rotor diameter and mass are 126 meters and 110000 kg, respectively, with a rated speed of 12.1 rpm. Besides, it has a cut-in and a cut-out wind speed of 3 and 25 m/s, respectively, where the rated wind speed is between these two with a value of 11.4 m/s. A conical linearly tapered tower with a length of 68 meters and diameters of 4 and 5.6 meters at the top and the end, respectively, is connected to the rotor and nacelle assembly (RNA). There is, also, a Transition Piece (TP), a concrete block with a mass of 666 t and dimensions of $4 \times 9.6 \times 9.6$ meters placed at the elevation 16.15 meters upward from mean sea level onto the jacket. A four-legged jacket with a length of 66.15 meters excluding the part penetrated the TP (70.15 meters, including TP) supports the RNA and tower in a water depth of 50 meters. It is fixed on the seabed using four steel piles with an outer diameter of 2.082 meters embedded through the seabed with a penetration depth of 45 meters. Figure 1 represents the corresponding OWT mentioned above.

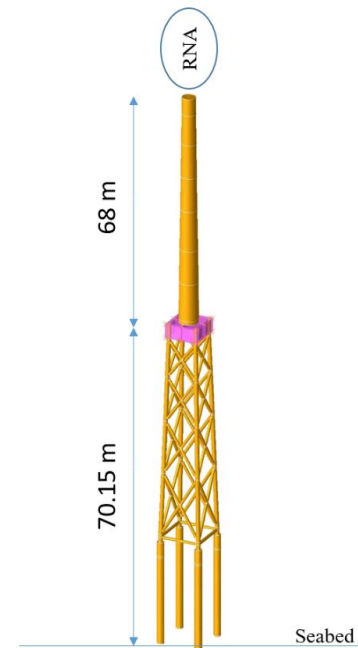


Figure 1. 5MW jacket-type OWT configuration

The soil profile used in this study is entirely based on the Upwind design basis presented by Fischer et al. [14] in which two different API-Sand [14-16] profiles, namely hard and soft, are presented. Soil parameters, including soil buoyant unit weight γ' , internal friction angle ϕ , and the undrained shear strength C_u within the

soil layers, can be found in table 1. The soft profile is taken into account here- as a conservative point of view. In order to simulate the OWT, FAST v.8 [17] is used, and as for the nonlinear soil-pile interaction analysis, the LPILE programme is adopted.

Table 1. Soil Profile Properties

Depth (m)	γ' (KN/m ³)	Φ (degree)	C_u (Pa)
0-3	10	36	-
3-5	10	33	-
5-7	10	26	60000
7-10	10	37	-
10-15	10	35	-
15-50	10	37.5	-

3. Dynamic Response Analysis

In order to obtain time histories of shear forces and flexural moments at leg bottoms in the FB model, dynamic response analysis is required. In this regard, FAST v.8 is used to simulate all aerodynamics and hydrodynamics aspects of environmental loads on OWT within the power production for 630 seconds. It should be noted that, according to Jonkman and Buhl [10] and Jonkman [18], the first 30 seconds are neglected to eliminate start-up transition behaviour as the system is assumed asymptotically stable. Since the ultimate purpose of the present study is fatigue damage analysis, from the first design situation, namely power production, second Design Load Case (1.2 DLC), which is the only one to be analysed in Fatigue Limit State (FLS), recommended by IEC 61400-3 [19] and given in the Upwind project design basis, must be considered for the simulations here. According to IEC 61400-3, concerning the 1.2 DLC; a Normal Turbulence model (NTM) with a turbulence intensity of 0.14 [14] as well as the joint probability distribution of the corresponding significant wave heights H_s , peak spectral period T_p and wind speed at hub height V_{hub} for the normal sea state are considered. The corresponding three-dimensional joint probability distribution is presented by Fischer et al.[14]. Moreover, based on the 1.2 DLC descriptions in IEC 61400-3, currents effects are neglected, and the wind and wave are aligned in terms of direction (co-directional). The structure is subjected to wave and wind loads from the direction of 0° [20, 21], as seen in figure 2. According to the Upwind project design basis, a lumped scatter diagram, including 17 different sea states, should be taken into account for fatigue analysis. However, as the primary purpose of the present study is estimating the apparent fixity length of the piles under operational load conditions and not to estimate the fatigue damage, all the 17 sea states are not considered as it is quite time-consuming. Instead, two sea states with the most frequency of occurrence within wind turbine service time were chosen based on the

joint probability distribution given by the Upwind design basis. Also, as the cut-out wind speed for the 5MW offshore wind turbine is 25 m/s, one more sea state with $V_{hub^1} = 24$ m/s is taken into consideration to cover the highest wind speed before the turbine shutdown. Table 2 shows the selected sea states properties. Regarding the wind spectrum, the Kaimal wind speed density spectrum is commonly used for offshore wind energy applications [22]. Also, the Power Law wind profile is used here for mean wind speed. Moreover, aerodynamic power is sensitive to blade pitch angle [23-25]. Once the wind speed exceeds the optimal 5MW turbine's speed, which is 11.4 m/s, the initial pitch angle of the blades (0°) will increase by the pitch controller relative to the corresponding wind speed. As a result, there will be different pitch angles that are proportional to the wind speeds up to the cut-out speed. These angles given by Jonkman et al. [13] are applied to the FAST's blades and rotor analysis module, namely ElastoDyn. As for the present study, only two wind speeds, 12 and 24 m/s are subject to change pitch angle to 3.83° and 22.35°, respectively.

Table 2. Sea States Properties

Sea state	V_{hub} (m/s)	H_s (m)	T_p (sec)
1	8	1	6
2	12	1.5	6
3	24	3.5	8

In order to generate stochastic waves and wind fields, wave and wind random seeds number for each particular simulation have to be changed. Turbulent wind fields are generated via TURBSIM [26] in which each random wind seed is changed by adding a small constant value for each simulation. Likewise, the same process is undergone in FAST to generate stochastic waves. As this procedure could be continued infinitely, a sufficient number of simulations need to be determined. Therefore, a statistical convergence criterion was considered, which could indicate the maximum number of simulations needed for each sea state as well as making our model uncertainty as least as a reasonable amount. Statistical criteria such as mean value, standard deviation, and skewness were investigated for each of the output results of simulations. Despite their variations were small comparing each other, it was not that convincing regarding our purpose. Hence the coefficient of variation (COV) of the output of the simulations –

Shear forces and Flexural moments – was obtained looking for results with equal or less than 5%. The results were reasonably acceptable after **eight simulations for sea state 1, eight simulations for sea state 2, and five simulations for sea state 3**. As it is

¹ Wind speed at hub height

shown in table 3, approximately all the values are less than 5%, which is quite reasonable in engineering problems.

Table 3. COV of the shear forces (F) and flexural moments (M) at jacket legs bottom

Sea state	F %	M %	F %	M %	F %	M %	F %	M %
1	5.11	4.93	3.78	3.67	3.42	3.71	2.75	3.02
2	1.61	1.70	1.09	1.19	1.33	1.50	0.91	1.08
3	2.10	2.20	1.13	1.12	1.26	1.45	0.74	0.88
Loc.	Leg bottom 1	Leg bottom 2	Leg bottom 3	Leg bottom 4				

4. Nonlinear Soil – Pile Interaction Analysis

As mentioned earlier, the investigation of the soil-pile interaction under applied lateral loads is required in order to find an adequate apparent fixity length of the piles. According to Randolph and Gourvenec [27] and Det Norsk Veritas (DNV) [28], Lateral loads applied to offshore wind turbines are broadly dominant for anchor piles and monopile foundations. In contrast, for jacket support structures, the piles are mainly axially loaded. Furthermore, it is also mentioned in DNV that in dynamic analysis for pile foundation systems, p-y curves are used to show soil-pile interaction, which means lateral loading would have a pivotal role in pile foundation systems. Thus soil-pile interaction analyses were conducted under lateral excitations using LPILE - known as a programme able to perform nonlinear soil-pile interaction analyses. Piles arrangement is shown in figure 2. The SubDyn module, which is responsible for dynamic structural analysis in FAST, can output either static components or dynamic components rather than the actual reaction loads, which cannot be computed efficiently for lattice structure with closed loops. The static components, however, are usually quite close to true reaction loads [29]. Thus, they are used here as shear forces and flexural moments time histories at the legs bottom yielded from FAST simulations of the FB jacket support structure. As the legs bottom are aligned with pile heads, the phrase “pile head” will be using in the following. More than 12 thousand contemporaneous shear forces and moments corresponding to each time step yielded from every single simulation and taking into account all of them was a laborious process. Therefore they were used to plot bivariate histograms via MATLAB [30] looking for the most frequent coupled shear force-flexural moment applied to the legs bottom. One of such histograms can be seen in figure 3.

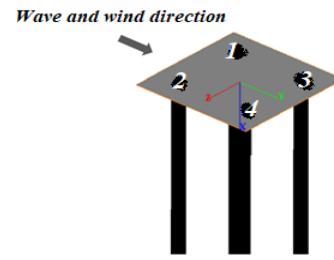


Figure 2. Piles arrangement to wave and wind direction

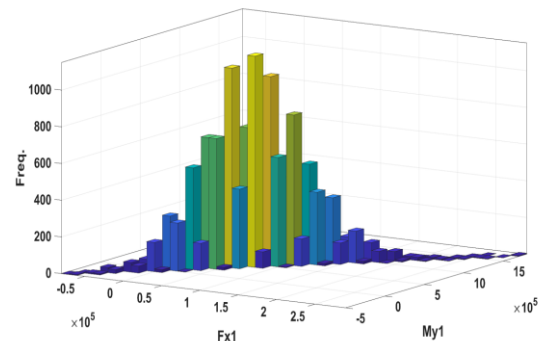


Figure 3. Sim.1, Sea state 1, coupled shear force (F)-flexural moment (M) histogram

The most frequent bins of the coupled shear forces and flexural moments containing more than one thousand values were found. The midpoints of the bins (F_x , M_y) are taken as the corresponding simulations indicator of the shear forces and flexural moments applied to each pile head. The midpoints are the obtained medians of the shear forces and moments relevant to each pile head corresponding most frequent range. Tables 4-6 represent the midpoint values for each simulation.

Table 4. Midpoint values - sea state 1

Simulation	Case	Leg bottom 1	Leg bottom 2	Leg bottom 3	Leg bottom 4
1	Shear force (N)	7.44E+04	8.55E+04	1.15E+05	1.15E+05
	Moment (N.m)	4.71E+05	5.35E+05	6.46E+05	6.44E+05
2	Shear force (N)	7.46E+04	8.47E+04	1.15E+05	1.15E+05
	Moment (N.m)	4.70E+05	5.33E+05	6.43E+05	6.45E+05

3	Shear force (N)	6.98E+04	6.99E+04	1.30E+05	1.30E+05
	Moment (N.m)	4.41E+05	4.41E+05	7.38E+05	7.31E+05
4	Shear force (N)	5.51E+04	6.99E+04	1.15E+05	1.29E+05
	Moment (N.m)	3.48E+05	4.40E+05	6.43E+05	7.32E+05
5	Shear force (N)	7.52E+04	7.02E+04	1.15E+05	1.15E+05
	Moment (N.m)	4.69E+05	4.44E+05	6.44E+05	6.44E+05
6	Shear force (N)	7.49E+04	5.52E+04	1.15E+05	1.15E+05
	Moment (N.m)	4.72E+05	3.47E+05	6.46E+05	6.44E+05
7	Shear force (N)	5.52E+04	7.52E+04	1.16E+05	1.15E+05
	Moment (N.m)	3.45E+05	4.72E+05	6.45E+05	6.42E+05
8	Shear force (N)	7.05E+04	7.02E+04	1.30E+05	1.10E+05
	Moment (N.m)	4.40E+05	4.41E+05	7.38E+05	6.11E+05

Table 5. Midpoint values - sea state 2

Simulation	Case	Leg bottom 1	Leg bottom 2	Leg bottom 3	Leg bottom 4
1	Shear force (N)	1.11E+05	1.11E+05	1.70E+05	1.51E+05
	Moment (N.m)	6.73E+05	6.73E+05	9.68E+05	8.44E+05
2	Shear force (N)	1.50E+05	1.10E+05	1.90E+05	1.70E+05
	Moment (N.m)	9.18E+05	6.70E+05	1.09E+06	9.65E+05
3	Shear force (N)	1.10E+05	1.10E+05	1.50E+05	1.50E+05
	Moment (N.m)	6.67E+05	6.68E+05	8.44E+05	8.39E+05
4	Shear force (N)	1.10E+05	9.11E+04	1.70E+05	1.50E+05
	Moment (N.m)	6.71E+05	5.49E+05	9.69E+05	8.43E+05
5	Shear force (N)	1.10E+05	1.10E+05	1.50E+05	1.50E+05
	Moment (N.m)	6.72E+05	6.73E+05	8.46E+05	8.39E+05

6	Shear force (N)	1.10E+05	1.10E+05	1.15E+05	1.15E+05
	Moment (N.m)	6.67E+05	6.71E+05	1.50E+05	1.50E+05
7	Shear force (N)	1.10E+05	1.10E+05	1.50E+05	1.50E+05
	Moment (N.m)	6.68E+05	6.72E+05	8.42E+05	8.41E+05
8	Shear force (N)	1.10E+05	1.11E+05	1.70E+05	1.51E+05
	Moment (N.m)	6.64E+05	6.72E+05	9.69E+05	8.41E+05

Table 6. Midpoint values - sea state 3

Simulation	Case	Leg bottom 1	Leg bottom 2	Leg bottom 3	Leg bottom 4
1	Shear force (N)	7.48E+04	4.60E+04	1.34E+05	1.05E+05
	Moment (N.m)	4.77E+05	2.85E+05	7.73E+05	5.83E+05
2	Shear force (N)	7.52E+04	4.66E+04	1.35E+05	1.35E+05
	Moment (N.m)	4.72E+05	2.87E+05	7.76E+05	7.74E+05
3	Shear force (N)	7.54E+04	4.59E+04	1.36E+05	1.34E+05
	Moment (N.m)	4.75E+05	2.87E+05	7.76E+05	7.66E+05
4	Shear force (N)	7.42E+04	7.56E+04	1.65E+05	1.06E+05
	Moment (N.m)	4.69E+05	4.77E+05	9.63E+05	5.77E+05
5	Shear force (N)	7.47E+04	7.47E+04	1.35E+05	1.34E+05
	Moment (N.m)	4.78E+05	4.71E+05	7.75E+05	7.69E+05

Midpoint values are used as load cases in the LPILE to simulate soil-pile interaction for each sea state. Piles lateral deflections and the pile heads stiffness matrices were yielded from LPILE. Lateral deflections of the piles within the penetration depth are shown in figures 4-7.

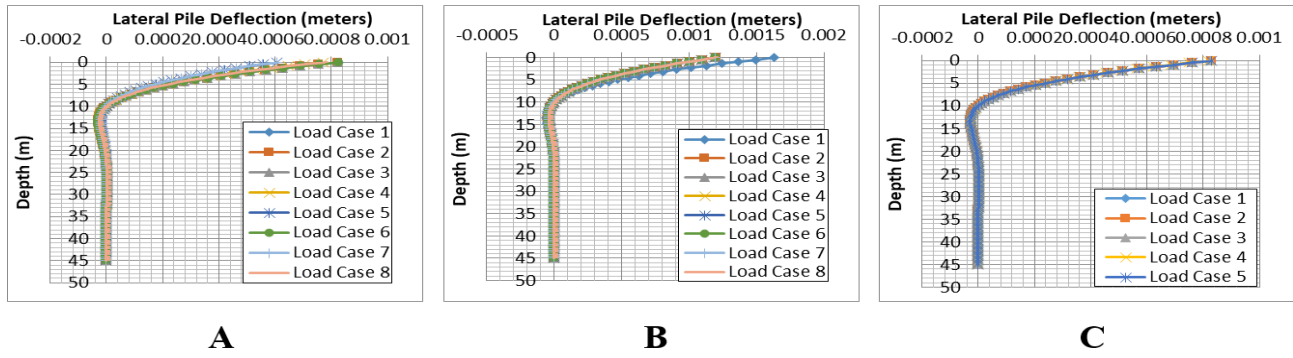


Figure 4. Pile 1 lateral deflections under sea state 1(A), 2(B), 3(C)

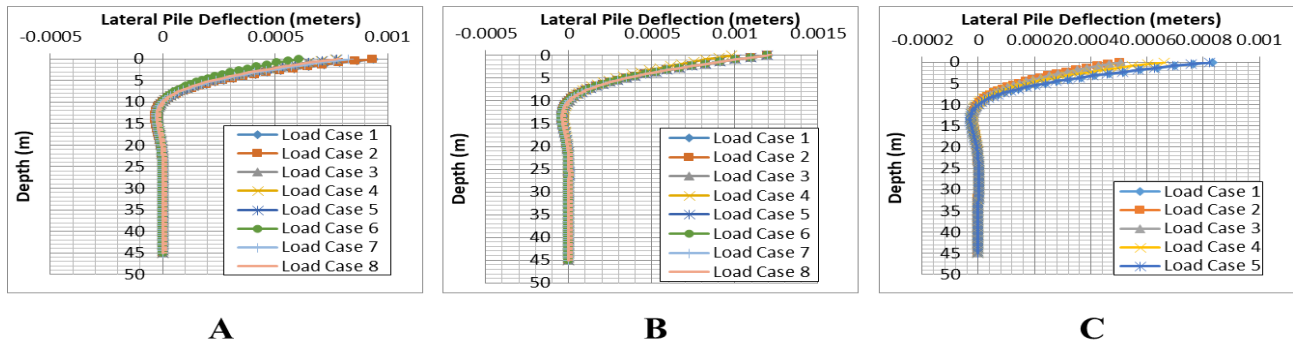


Figure 5. Pile 2 lateral deflections under sea state 1(a), 2(b), 3(c)

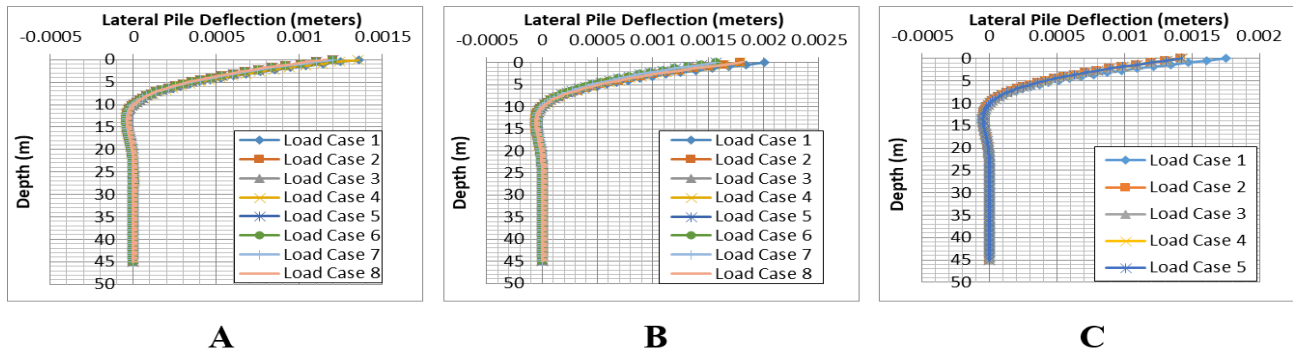


Figure 6. Pile 3 lateral deflections under sea state 1(A), 2(B), 3(C)

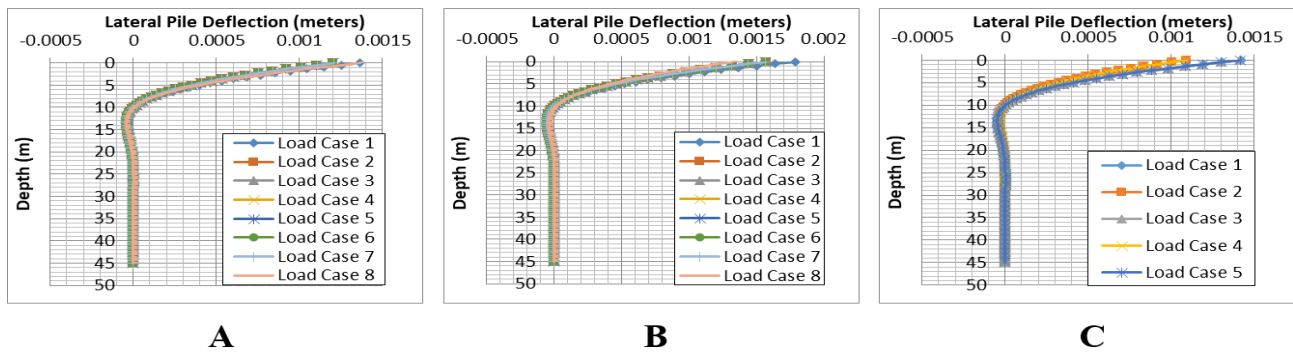


Figure 7. Pile 4 lateral deflections under sea state 1(a), 2(b), 3(c)

As it was mentioned earlier, in the AF model, the pile is presumed to be penetrated the seabed and fixed at a level where the same behaviour of the pile embedded in real soil is expected. As only translational and rotational displacements are involved, the pile heads 2×2 stiffness matrices (Eq.1) are obtained via LPILE. Moreover, it can be seen that the piles' deflections are quite small to the piles' lengths. Thus the Euler-Bernoulli beam theory would apply to the piles. As a result, the obtained matrices can be equalized to a two degree of the freedom stiffness matrix of a cantilevered Bernoulli beam (Eq.2) to find the apparent fixity length of the piles.

$$\begin{bmatrix} K_{22} & K_{23} \\ K_{32} & K_{33} \end{bmatrix} \begin{bmatrix} w \\ \theta \end{bmatrix} = \begin{bmatrix} F \\ M \end{bmatrix} \quad (1)$$

$$\begin{bmatrix} \frac{12EI}{L^3} & -\frac{6EI}{L^2} \\ \frac{6EI}{L^2} & \frac{4EI}{L} \end{bmatrix} \begin{bmatrix} w \\ \theta \end{bmatrix} = \begin{bmatrix} F \\ M \end{bmatrix} \quad (2)$$

As for equations 1 and 2, w , θ , F , M are translational displacement, rotational displacement, applied shear force, and flexural moment, respectively. Also, K_{22} , K_{23} , K_{32} , K_{33} indicate stiffness coefficient related to shear force, coupled shear force-moment, coupled moment-shear force, and moment applied to the pile head taking the values 434775 KN/m, 1837296 KN/rad, 1836188 KN-m/m, 12951078 KN-m/rad, respectively. It should be noted here, as the piles' deflections were quite small under each state, the stiffness coefficients – obtained from LPILE – were the same for each sea state. The bending stiffness (EI) obtained from LPILE, also, is held constant along the piles and takes a value of $4.02 \times 10^7 \text{ KN.m}^2$.

5. Results and Discussion

Pile heads, and cantilevered Euler-Bernoulli beam stiffness matrices (Eq.1, Eq.2) were equalized assuming that applied shear forces and flexural moments (F , M) to the pile heads are the same in both FB jacket and a flexible one. Nonetheless, the loads experienced by the FB model at the legs bottom (pile heads) are not the same as those applied to a flexible model in reality. According to Bush and Manuel [2] – given that the OC4 project soil properties – the statistical criteria such as standard deviations and mean values of shear forces and flexural moments at pile heads are altered less than one per cent comparing FB model to flexible model. As a result, the translational and rotational displacements (w , θ) are taken similar for both stiffness matrices above. Hence the first terms of Eq.1 and Eq.2 should be equal, and they can be written as Eq.3.

$$\begin{bmatrix} \frac{12EI}{L^3} & -\frac{6EI}{L^2} \\ -\frac{6EI}{L^2} & \frac{4EI}{L} \end{bmatrix} = \begin{bmatrix} K_{22} & K_{23} \\ K_{32} & K_{33} \end{bmatrix} \quad (3)$$

Eventually, the apparent fixity lengths (L) corresponding to each stiffness coefficient were obtained which are given in table 8

Table 7. Estimated apparent fixity lengths for different stiffness coefficients

Stiffness coefficient	Apparent fixity length (m)
K_{22}	10.35 (~ 5D)
K_{23}	11.46 (~ 5.5D)
K_{32}	11.45 (~ 5.5D)
K_{33}	12.41 (~ 5.96D)

Modal analyses were performed via BMODES [31]- a Finite Element (FE) code for modal analysis of blades and tower- for different apparent fixity lengths looking for the natural frequency of the structure. The fixity length values recommended by Barltrop and Adams, 6D for general calculations, and 8D as a mean value for soft soil profiles, are considered as well as the values yielded from this study – presented in table 7. Modal analysis results are presented in Table 8.

Table 8. Natural frequencies of the structure for different pile fixity length

Apparent Fixity Length (m)	Structure Natural Frequency (Hz)
6D (12.46)	0.309
8D (16.64)	0.303
5D (10.35)	0.430
5.5D (11.46)	0.426
5.5D (11.45)	0.428
5.96D (12.41)	0.311

According to the Upwind final report [32], the structural natural frequency of the OC4 offshore wind turbine supported by a jacket should be in a range between 0.222 Hz and 0.31 Hz. Apart from the fixity length of 6D and 8D, 5.96D (12.41 m) is the only fixity length, which leads to a natural frequency appropriate to the interval mentioned above. It can be seen that it is the minimum apparent fixity length of the piles that would be adjusted concerning the corresponding natural frequency of the structure.

6. Summary and Conclusions

This paper presents a method to estimate adequate apparent fixity length for the piles in OC4 OWT under lateral loading, taking into account nonlinear soil-pile interaction. Initially, a FB jacket substructure for OC4 OWT is assumed and simulated under Normal load conditions using FAST to obtain the dynamic response of the structure. Subsequently, load reactions at the legs bottom are considered as applied loads to the pile-heads in order to conduct nonlinear soil-pile interaction analysis in a geotechnical programme, namely LPILE. As a result, piles lateral deflection and stiffness matrices of the pile heads are obtained. Pile heads stiffness matrices are individually compared with the stiffness matrix of a cantilevered Bernoulli beam at its free head to find the apparent fixity length of the piles. Concerning each stiffness coefficient, a particular fixity length is obtained. It observed that the piles had deflected increasingly up to 13 meters of depth below the seabed. Afterwards, the deflection descended until they have almost returned to the preloaded condition. Additionally, several modal analyses were conducted for the structure considering different piles' fixity length. Apart from fixity lengths of 6D and 8D, which are extensively used in literature, 5.96D (12.41 m) was the only fixity length, which leads to a natural frequency compatible with the allowable interval given by OC4 OWT design basis. In other words, according to the natural frequencies, the minimum apparent fixity length for lateral loading condition was considered as $L_{AF} = 12.41$ meters downward the seabed. Besides, among the obtained fixity lengths, this level is the closest value to 13, where the piles stop to deflect. Therefore, it can be concluded that the adequate piles' apparent fixity length for the OC4 OWT under lateral loading during power production can be chosen from one of the following values: 6D (12.46m) and 8D (16.64m), recommended by Barltrop and Adams, and the minimum length of 5.96D (12.41m) proven in this study and they are all suitable assumptions applicable to fatigue analysis when lateral loading is dominant.

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List of Symbols

EI	Bending stiffness
k	Stiffness coefficient
W	Translational displacement
θ	Rotational displacement
F	Shear force

M	Flexural moment
H_s	Significant wave height
T_p	Spectral period
V_{hub}	Wind speed at hub height
COV	Coefficient of variation

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