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ScienceDirect

Energy Procedia 94 (2016) 347 – 356

Energy Procedia

13th Deep Sea Offshore Wind R&D Conference, EERA DeepWind'2016, 20-22 January 2016, Trondheim, Norway

Influence of Soil Parameters on the Fatigue Lifetime of Offshore Wind Turbines with Monopile Support Structure

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Abstract

Designing support structures for offshore wind turbines is a complex task as these are highly dynamic systems subjected to long-term cyclic loads with variable amplitude. Long-term cyclic loading may cause stiffening or softening of the soil around the pile foundation of an offshore wind turbine, which leads to variations in the foundation stiffness and accumulated permanent rotation of the pile. Although variations in the foundation stiffness can negatively impact the fatigue life, the long-term variability of the soil conditions is normally not considered in the fatigue damage assessment. The main objective of this study is the investigation of the impact of changes in soil parameters on the fatigue lifetime for an offshore wind turbine founded in loose sand. For this purpose, a generic monopile based offshore wind turbine with flexible foundation model was used. The soil-pile interaction was modeled with a distributed spring model using nonlinear API *p-y* curves. Integrated analyses in the time domain were performed and fatigue damage was assessed in terms of a damage equivalent bending moment at mudline. The fatigue lifetime varies between -9 percent and +4 percent when considering changes in soil conditions, depending on the assumption of soil softening or stiffening, respectively. These results indicate that changes in soil parameters should be taken into account in the fatigue damage calculations of offshore wind turbines for more precise fatigue lifetime estimation. Moreover, it is emphasized that more accurate modeling of soil-pile interaction is required in the design and optimization of offshore wind turbines.

Peer-review under responsibility of SINTEF Energi AS

Keywords: Offshore wind turbines; fatigue lifetime estimation; soil-pile interaction; p-y curves; cyclic loading

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Peer-review under responsibility of SINTEF Energi AS
doi:10.1016/j.egypro.2016.09.194

1. Introduction

Among the different concepts for offshore wind turbines (OWTs) support structures, the monopile is a preferred solution for shallow and intermediate water depths. Approximately 75% of currently installed OWTs are supported by monopile structures. Fatigue is typically the design driver, since OWTs are exposed to a significant source of quasi-periodic excitations from wind and waves. Fatigue assessment is, therefore, mandatory and due to time history depended effects and structural nonlinearities, the most accurate way is still based on structural analysis in the time domain. In fact, current standards prescribe that the analysis of OWTs is performed in the time-domain [1].

Structural analysis is based on simulations of several design load cases [2] and thus requires a numerical model of the OWT. Although OWTs are typically designed for a lifetime of 20 years, long-term variability of the environment is not considered. Especially changes in soil conditions play a crucial role for the design of an OWT. Support structures such as monopiles are often designed in a soft-stiff manner, where the first structural frequency (fore-aft mode) of the structure is placed in the range above the 1P (rotational) and below the 3P (blade-passing) excitation frequency. This criterion is not dictated by guidelines, but commonly used in design practice, since a structural frequency too close to an excitation frequency will lead to resonance and greatly increased fatigue damage. Cyclic loading may cause accumulated pile displacements and stiffening or softening of the soils around the pile, leading to variations in the foundation stiffness, thereby changing the structural frequencies of the OWT. This can bring structural frequencies closer to excitation frequencies, which would result in increased dynamic amplification of the response, an enhancement of fatigue damage, and a reduction in the intended fatigue lifetime.

Changes in the foundation stiffness and accumulated displacements due to long-term cyclic loading have been observed in small-scale tests [3-6] and in centrifuge tests [7]. Kallehave et al. [8] presented full-scale measurements of a storm event where the measured fundamental frequency of the OWT was temporally reduced, and related it to a possible change in the pile stiffness. Despite the fact that few full-scale measurements are available, these do not cover a sufficiently long period to evaluate the effects of long-term cyclic loading.

Several numerical studies have aimed to provide an insight into how variations of the soil properties influence the dynamics of the OWT. Zaaijer [9] investigated the possible deviations in the fundamental frequency due to uncertainties related to the parameter estimation, the location and the design lifetime. For a monopile foundation, a maximum deviation in the fundamental frequency of 6% was found for a variation in the internal friction angle of the soil of ±10%. Bisoi and Haldar [10] performed a parametric study on an OWT founded in a clay soil profile using *p-y* curves to represent the soil response. Damgaard et al. [11-12] studied how changes in soil properties may affect the fatigue life using a lumped-parameter model.

Following previous work, our study assesses the impact of soil parameter variability on fatigue damage and estimates the fatigue lifetime of an OWT subject to changes in soil conditions over the designed lifetime. Focus of this study is, therefore, changes in soil properties over the lifetime, instead of uncertainties of soil parameters in the design phase of the OWT.

Nomenclature

A	factor for cyclic or static loading	p_u	ultimate resistance
D	pile outside diameter	p	soil reaction
E_s	initial modulus of subgrade reaction	S	stress amplitude
i	cycle index	y	pile deflection
k	rate of increase with depth of E_s	z	depth below mudline
m	material parameter	γ'	effective unit weight of soil
N	number of cycles	ϕ'	internal friction angle
		θ	tilt angle

2. Modelling of soil reaction under laterally loaded piles in sand

The soil-pile interaction for laterally loaded piles in sand is commonly modelled by means of *p-y* curves as defined by the American Petroleum Institute (API) [13]. *P-y* curves describe the soil reaction, *p*, as a function of pile

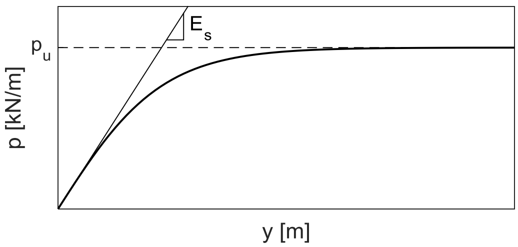

Fig. 1. P-y curve for sand.

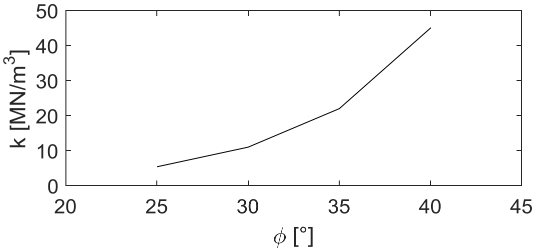

Fig. 2. Rate of increase of initial modulus of subgrade reaction plotted against the internal friction angle

deflection, y. They are nonlinear and depend on soil type, specific depth, and pile properties. Fig. 1 shows a typical p-y curve for sand. The resistance-deflection (p-y) relationship is determined by the initial modulus of subgrade reaction, E_s, the ultimate resistance, p_u, and the depth below the mudline, z. It is defined in [13] by

$$p = A \times p_u \tanh\left[\frac{E_S}{A \times p_u} y\right] \tag{1}$$

and

$$E_S = k \times z \tag{2}$$

where A is a factor to account for cyclic or static loading conditions and k is the rate of increase with depth of initial modulus of subgrade reaction. The parameter k can be related to the relative density of sand and the internal friction angle, ϕ' (see Fig. 2). It describes the stiffness of the p-y curve, while the ultimate resistance stands for the strength. The latter is also affected by the internal friction angle and may be calculated for shallow depths by Equation (3) and for deep depths by Equation (4).

$$p_{us} = (C_1(\phi')z + C_2(\phi')D)\gamma' z \tag{3}$$

$$p_{ud} = C_3(\phi')D\gamma' z \tag{4}$$

Where D is the outside diameter of the pile, γ' is the effective unit weight of soil, and the coefficients C_1, C_2, and C_3 are functions of ϕ'. More details and a comprehensive overview of models for response of soil can be found in [14].

The p-y method has been successfully applied for pile design in the oil and gas industry for many decades, showing a low failure rate for piles in-service [15] and it is recommended by the DNV standard for estimation of the lateral pile capacity in ULS analyses [1]. It has the advantage that it can represent the nonlinearity of the soil and it is computationally effective. However, the applicability of the p-y formulation to predict pile behaviour of OWTs has been questioned [16-18]. One of the main shortcomings is that the p-y method was derived and verified for different pile geometries and applied loading than the ones present in OWT. Under relatively small vertical loads and large overturning moments, large diameter piles show a rigid behaviour with a clear rotation point, in opposition to the flexible pile behaviour assumed in the p-y method. In addition, the method was developed following a static approach, and the effect of long-term cyclic loading on the spring strength and stiffness is not explicitly considered. Hald et al. [19] compared the measured and the predicted bending moments using p-y curves for a pile in sand at the Horns Rev wind farm; and concluded that the soil response was underestimated. A more accurate method adapted for large diameter piles that can account for the effects of long-term cyclic loading is needed.

There exist models that can reproduce the soil behavior under cyclic loading as a function of the soil properties, the stress level and the number of load cycles [20-23]. These models generally predict accumulated displacements and stiffness and strength degradation as a consequence of cyclic loading. A limitation in the application of these models is that a numerical tool, for instance solid finite element analyses, is needed to integrate the soil behavior at stress level to foundation behavior. In addition, an idealized cyclic load history at mudline is required [24]. At present, the efficiency of this integration step is not sufficient to employ these models in time-domain analyses of OWTs. Thus, the soil reaction in this study has been modelled by means of API *p-y* curves and simplified models are used to account for changes of soil conditions over lifetime.

3. Numerical model of offshore wind turbine

Results presented in this paper are based on simulations with the generic OWT used within Phase II of the OC3 project [25]. The OWT is located in a water depth of 20 m and consists of a monopile support structure with the NREL 5 MW baseline turbine atop. A tower with a linearly tapered diameter and thickness is mounted on top of the monopile which has a constant diameter of 6 m and a constant thickness of 0.06 m. The portion of the monopile above the mudline has a length of 30 m and the portion below the mudline is referred to as the pile foundation. Fig. 4 illustrates the model of the OWT with monopile support structure including the pile foundation.

The pile foundation of the monopile support structure has a penetration depth of 36 m and has material properties and dimensions equal to the portion above the mudline. The numerical model consists of cylindrical beam elements with hollow cross-section using the real length and properties (dimension and material) of the pile foundation.

The model for the soil-pile interaction is adapted from Passon [26] and uses lateral springs distributed in intervals of 1 m along the pile (see Fig. 4). The springs are uncoupled and their stiffness is based on the nonlinear API *p-y* model for sand as described in Section 2. Interconnected *p-y* springs are used for the model, which means that the soil springs work in the radial direction with respect to the pile axis and unidirectional with the applied load. This enables a more accurate calculation of the soil-pile interaction than using springs in distinct directions, especially when the loading is misaligned to the main loading direction (see Fig. 3). Parameters and properties used for the soil profile are listed in Table 1.

Table 1. Parameters and properties for soil profile (reference case)

Layer	Depth	k_{ref}	ϕ'_{ref}	γ'_{ref}
Layer 1 (sand)	0-5 m	16287 kN/m^3	33.0º	10 kN/m^3
Layer 2 (sand)	5-14 m	24430 kN/m^3	35.0º	10 kN/m^3
Layer 3 (sand)	14-36 m	35288 kN/m^3	38.5º	10 kN/m^3

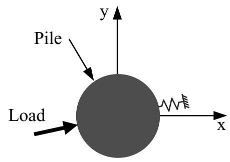

Fig. 3. Interconnected springs (top view)

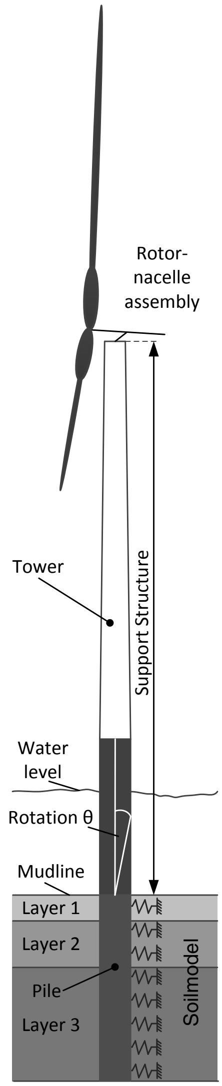

Fig. 4. OWT used in this study

4. Variations in soil conditions

Soil parameters provided in Section 3 serve as the reference case for this study (ref), while this section describes the variation of soil parameters conducted within this study.

4.1. Rate of increase with depth of initial modulus of subgrade reaction

The effect of a change in the soil stiffness is studied by means of varying parameter *k* (see Eqn. 2). LeBlanc et al. [4] developed a method to estimate non-dimensional pile stiffness for the first and the Nth-cycle as a function of the load characteristics, the relative density and the number of loading cycles. For sand with an internal friction angle of 35º, this method predicts that the non-dimensional pile stiffness can be doubled after 10^7 cycles. This agrees well with the non-dimensional pile stiffness ratios from centrifuge tests presented in [7]. In our study, the *k* reference value is increased up to 100% (see Table 2).

Despite an overall increase in pile stiffness in sandy soils due to long-term cyclic loading, during storm events the pile stiffness can be reduced. Full-scale measurements in Horns Rev II [8] revealed that during a storm event, with wind speeds ranging from 20-40 m/s, the measured fundamental frequency of the system (1st fore-aft mode) was temporally reduced by 5%. The change in frequency was correlated to a possible reduction of the pile stiffness of 50%, and was observed for displacements in the range of 0-0.025% of the pile diameter. At that level of displacements, the API *p-y* curves do not show nonlinearity, and the soil stiffness is controlled by k. In order to investigate the effect of reduced pile stiffness during a storm event, the k reference value was decreased by 70%.

Depending on the load amplitude, the number of load cycles and the pile behavior (rigid or flexible), the stiffening can affect only the top part of soil surrounding the pile or can affect also deeper soil layers. This issue has been studied by implementing three different classes of structural models. These are:

- K1: Variation of k affects only the first soil layer.
- K2: The first and the second layer are scaled with the same factor, while the third layer uses the reference values.
- K3: All three layers are simultaneously scaled with the same factor.

Models of class K1 and K2 represent the expected behavior for a flexible pile subjected to low-amplitude and high-amplitude lateral cyclic loading, respectively. Models of class K3 cover the expected pile behavior for rigid piles.

4.2. Internal friction angle

The effect of a change in the soil strength was studied by varying the internal friction angle of the sand, ϕ'. Cuéllar et al. [3] suggested that for piles installed in loose sand, long-term drained cyclic lateral loading can lead to densification of the sand around the pile. A maximum relative density of 80% is assumed for the first and the second soil layers, which can be correlated to peak drained friction angles of 43º and 42º through the consolidation stress [27]. The maximum densification will most likely not be reached uniformly around the pile and the maximum value can be seen as an upper bound. It is not expected that the third layer densifies. In a similar way to Section 4.1, two different classes of structural models for the variation in internal friction angle have been considered:

- F1: Variation of internal friction angle affects only the first soil layer.
- F2: The first and the second layer are scaled with the same factor, layer three uses the reference values.

4.3. Accumulated permanent rotation

Laboratory and model tests have shown that cyclic loading above a certain threshold causes permanent deformation in the soil [28]. This will accumulate to permanent displacements and permanent rotation if the loading is not purely symmetric. An OWT is, therefore, prone to permanent rotations at mudline, due to the cyclic and nonsymmetrical nature of the loads acting on it [7, 29].

The current API *p-y* formulation is based on elastic springs, and cannot account for the effect of accumulated (non-elastic) deformations and rotations. Furthermore design guidelines do not recommend a specific method to account for the accumulated rotation. In this study the accumulated rotation was modeled by tilting the initial geometry of the pile by an angle θ (see Fig. 4). The maximum tilt angle studied has been chosen based on the threshold magnitude of 0.5° allowed by current standards [1]. Using a step size of 0.125°, additional structural models with four different tilt angles for the OWT, referred to as model class T1, have been defined. The soil properties for these models are equal to the reference case and do not vary with the rotation.

All soil parameters with corresponding scale range, the accumulated permanent pile rotation and step sizes are summarized in Table 2. The variation of the reference model leads to in total 68 numerical models of the OWT.

Table 2. Scale range for soil parameters and permanent rotation of pile

Parameter		Min	Max	Step size	Variations	Class	Total
Scale range for initial modulus of subgrade reaction	k/k_{ref}	0.3	2	0.1	17	K1, K2, K3	51
Scale range for internal friction angle	ϕ'/ϕ'_{ref}	1	1.3	0.05	6	F1, F2	12
Accumulated permanent rotation	θ	0°	0.5°	0.125°	4	T1	4

5. Fatigue lifetime estimation

5.1. Load analysis

The flexible multibody simulation tool Fedem Windpower (Version R7.1.4, Fedem Technology AS) was used to perform the load analysis of the OWT in the time domain. Fedem Windpower allows for an integrated dynamic analysis of the OWT under combined aerodynamic and hydrodynamic loads and was verified in the OC4 project [2]. Simulations were performed for operational load situations in accordance with the current standards [1] for wind speeds between 4 m/s and 24 m/s. A step size of 2 m/s was used leading to a set of 11 load cases. These are some of the most important load cases for fatigue analysis. Properties for corresponding turbulence models and sea states as well as environmental conditions and probability of occurrence were taken from the UpWind Design Basis [30]. Simulations were performed for aligned wind and wave direction with 600 seconds duration excluding transients.

5.2. Fatigue damage assessment

This study compares fatigue damage relative to the damage in the reference model of the OWT. Thus, it is sufficient to assess fatigue damage in terms of damage equivalent loads (DELs). These are constant-amplitude load ranges that would cause an equivalent amount of damage as the original variable-amplitude load time series. DELs are calculated as

$$DEL = \left(\sum_{i=1}^{N} \frac{S_i^m}{N} \right)^{1/m} \tag{5}$$

Where N is the number of load cycles applied, S_i is the load range amplitude at cycle i, and m is a material parameter, which is set to 4.0 in order to match the properties of the monopile support structure.

Among the cycle counting techniques, the rainflow-counting algorithm [31] has been shown to match experimental results well and was used to determine the number of cycles, N, and the corresponding load amplitudes, S. Using the probability of occurrence of wind speeds as stated in [2], a DEL at mudline accumulated over the lifetime of the OWT can be obtained, which serves as an estimate of the fatigue lifetime in this study.

5.3. Variability of soil parameters over lifetime

Four scenarios were considered in order to investigate the impact of changes in soil parameters on the fatigue lifetime. The scenarios include a best case (S1) as well as a worst case (S4), where the rate of increase with depth of initial modulus of subgrade reaction, the internal friction angle, and the permanent rotation is changed immediately after the installation of the OWT (for example caused by a big storm). In addition two scenarios are used with a linear increase (S2) and a linear decrease (S3) of the soil parameters of the reference case towards the values equal to the best and worst case scenarios, respectively (see Table 3 and Fig. 5).

Table 3. Parameter variation for different scenarios

Scenario		Class	k/k_{ref}	ϕ'/ϕ'_{ref}	θ
S1	Best case	F2+T1	2.0	1.3	0°
S2	Linear increase	Lin. F2+T1	1-2.0	1-1.3	0°
S3	Linear decrease	Lin. K3+T1	1-0.3	1	0.5°
S4	Worst case	K3+T1	0.3	1	0.5°

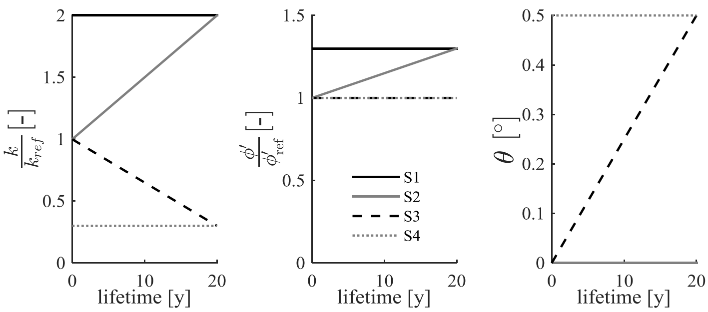

Fig. 5. Scaling of k, ϕ', and θ over design lifetime

6. Results

The 68 numerical models of the scaled reference OWT and the reference OWT itself were analysed each with the set of 11 load cases, leading to in total 759 load simulations and a comprehensive database of results. This paper shows results that are considered most interesting for the fatigue lifetime estimation.

6.1. Modal analysis

Following the criterion for soft-stiff design, the first structural frequency of the OWT in this study has to be between the rotational frequency of the rotor (0.20 Hz) and the tower passage frequency of the blades (0.35 Hz). The first structural frequency of the unscaled model was determined to be 0.2398 Hz and the scaled models change this frequency in a range from -3% to +2%, leading to a minimum frequency of the first fore-aft mode of 0.2304 for model of class K3 with a scale factor of 0.3 and a maximum of 0.2441 for model of class F2 with a scale factor of 1.3. Frequencies for the second fore-aft mode of the turbine model are with at least 1.245 Hz, well above the tower passing frequency of the blades. The changes in the first fore-aft frequency are shown in Fig. 6. The figure does not include results for models with accumulated permanent rotation (T1), since the reference soil model is used for this class of modification, which does not influence the structural frequencies.

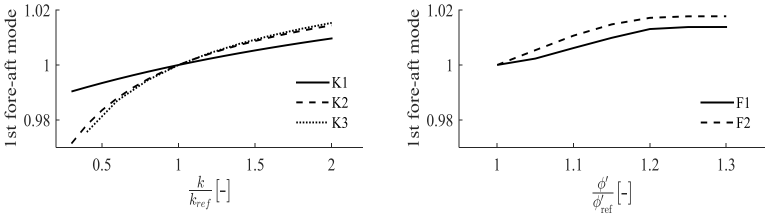

Fig. 6. 1st structural fore-aft eigenfrequency of modified models normalized to unscaled model.

6.2. Damage equivalent bending moment at mudline

The values for DEL accumulated over lifetime plotted against the scale factor (class K and F) and tilt angle (class T) are shown in Fig. 7. Results are normalized to the accumulated DEL of the reference model. The figure shows a clear trend for scaling k as well as for an increase of ϕ'. For both model classes the DEL accumulated over lifetime decreases and the decrease or increase of the DEL is more significant the more layers are included in the scaling. Thus, the highest changes in accumulated DEL are recorded for K3 (+9%) and F2 (-4%). The results are in agreement with [11], where a reduction of 50% in the foundation stiffness leads to an increase of 12% in the DEL at mudline. Fig. 7 also shows that scaling the rate of increase with depth of initial modulus of subgrade reaction of the bottom layer of the soil does not influence the results significantly. The differences between K1 and K2 are larger than differences between K2 and K3. Considering a permanent rotation of the OWT influences the accumulated DEL less than the scaling of soil parameters. Although an accumulated rotation of 0.5º is used, corresponding to the limit value for SLS [1], the maximal increase of the DEL is below 1%. The trend of the curve for T1 indicates a modest linear increase over the increase of the tilt angle.

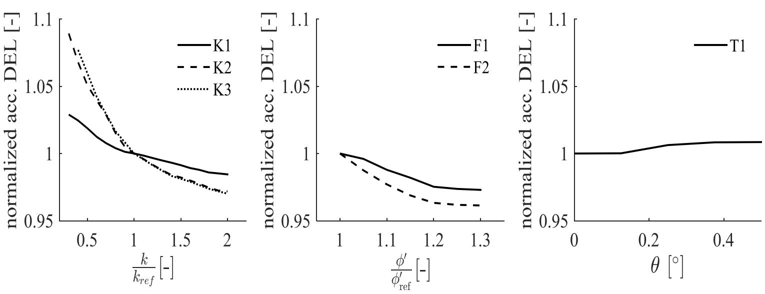

Fig. 7. Accumulated DEL at mudline normalized to unscaled model.

6.3. Maximal damage equivalent bending moment along the pile

The mudline bending moment does not always define the highest fatigue damage for pile foundations. In fact, the highest fatigue damage along the pile can be expected slightly below the mudline. For the reference model of the OWT subject to this study it is found to be in a depth of -5 m with respect to the mudline. Generally, the highest fatigue damage in terms of DEL moves from a position of -9 m below the mudline (for K3 with the smallest scale factor of 0.3) up to -4 m (for K3 and F2 and the corresponding largest scale factors). The position is also influenced by the load case. Higher aerodynamic and hydrodynamic loads typically move the position of the highest DEL slightly further down. Variations in the rotation of the pile do not significantly influence the position.

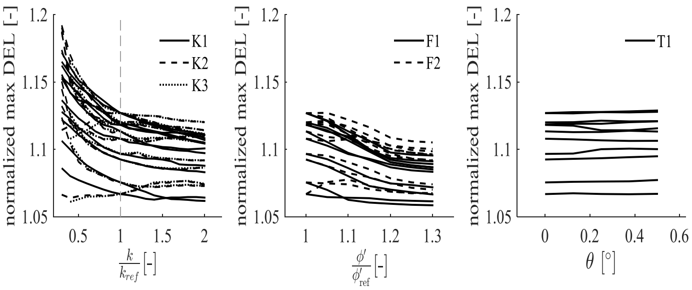

Fig. 8. Ratio of maximum DEL along the pile and DEL at mudline. Each line represents one of the 11 load cases.

More important than the position is the actual difference compared to the mudline bending moment. For this purpose time history responses from bending moments along the pile foundation were used to calculate a DEL. The values are compared to the DEL at mudline and the ratio is plotted over the different classes of modified OWT models in Fig. 8. Each line represents a single load case, starting with the load case with the smallest wind velocity being the bottom curve of the plot and the load case with the highest wind velocity being the top curve of each plot.

The highest difference between the maximal DEL along the pile and the mudline DEL occurs for models with low scale factors and reaches values up to 19.2% (K3 with scale factor 0.3). Differences between maximal DEL and mudline DEL become smaller for larger scale factors, which can be explained by the fact that the position of the maximal DEL moves closer to mudline. The differences for OWT models of class T1 change only marginally, which matches the above reported results regarding the position of the maximal DEL along the pile.

6.4. Influence on fatigue lifetime

Fig. 9 shows the fatigue damage in terms of DEL at mudline per year normalized to the fatigue damage of the reference model. In the worst case scenario the fatigue damage per year is approximately 1.1 times higher compared to the reference model, which will reduce the lifetime of the OWT by 1.79 years. Results for the three additional scenarios and their estimated impact on the fatigue lifetime are listed in Table 4.

Table 4. Fatigue lifetime (LT) for different scenarios

Scenario		Class	LT [y]
S1	Best case	F2+T1	20.80
S2	Linear increase	Lin. F2+T1	20.35
S3	Linear decrease	Lin. K3+T1	19.21
S4	Worst case	K3+T1	18.21

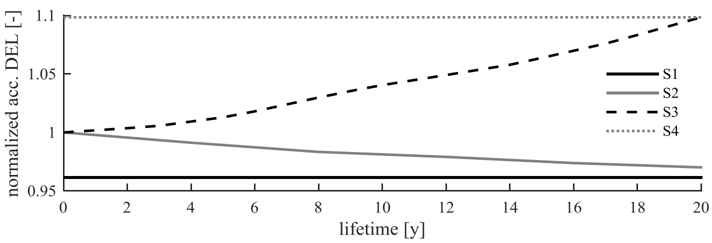

Fig. 9. Impact on the normalized accumulated DEL at mudline.

7. Discussion and Conclusion

This study has its main objective in investigating the impact of changes in soil parameters on the fatigue lifetime for OWTs. For this purpose, a comprehensive parameter study was carried out with a monopile supported OWT founded in loose sand. API *p-y* curves were used in order to model the soil reaction. The damage equivalent bending moment at mudline was used as an indicator for the fatigue lifetime of the OWT. Based on the obtained results for this DEL, four different scenarios for variation in soil conditions over the lifetime of the OWT were applied. These scenarios consider a change of soil properties within a reasonable range according to interpretation of short-term full-scale measurements and small-scale tests from the literature. Changes in soil properties were assumed immediately after the installation (Scenario 1 and 4) and with a linear development (Scenario 2 and 3). These assumptions were made mainly due to a lack of long-term full-scale measurements documenting changes in soil properties over the lifetime of an OWT.

Despite the current lack of a more accurate alternative in modelling soil-pile interactions in the time-domain, the selected results show good agreement with previous studies in terms of modal analysis and DELs at mudline [8, 11].

Commonly, the fatigue damage caused by the bending moment at mudline is considered as the governing factor for a monopile design. Interestingly, the study showed that higher fatigue damage may occur slightly below the mudline. However, this study followed the common design practice and used the damage equivalent bending moment at mudline for the fatigue lifetime estimation of the OWT.

Results of this study indicate that variability in soil conditions during the lifetime significantly influences the structural analysis of an OWT. Considering a best and a worst case scenario, the initial fatigue lifetime of 20 years varies in a range between 18.21 and 20.80 years. Variability in soil conditions during the lifetime of an OWT should, therefore, be addressed in the design and optimization process.

Further work and research is required in order to estimate fatigue lifetime of OWTs more accurately. Firstly, it is necessary to understand the behavior of soil in the light of full-scale measurements of OWTs. Based on this improved understanding of soil behavior, models that account for changes in soil properties during the lifetime and that are suitable for an integrated analysis of the OWT in time domain can be developed.

Acknowledgements

Support by the Norwegian Research Centre for Offshore Wind Technology (NOWITECH FME, Research Council of Norway, contract no. 193823) is gratefully acknowledged. In particular we thank Fedem Technology AS for support. In addition, we acknowledge financial support by the Norwegian Research Council through project *Reducing cost of offshore wind by integrated structural and geotechnical design (REDWIN)*, Grant No. 243984.

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