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Load characteristics of axially loaded jacket piles supporting offshore wind turbines

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Summary

Piled foundations are the most common form of offshore foundation, transferring both tensile and compressive loads into the seabed. When these foundations are used for offshore wind turbines, new loading situations are to be taken into account. In order to obtain reliable assessment it is necessary to know and understand the magnitude, loading history and loading frequency of design loads occurring during life of the offshore wind turbine.

It is shown in this paper that load characteristics often discussed in this context (e.g. the loading history from turbine operation with up to 10^9 load cycles during 20 years) may not be the most important design situation and that attention should be drawn to other loading conditions, e.g. fault or storm load cases.

1 Introduction

Substructures and their foundations for offshore wind turbines as e.g. described in [Seidel, 2007] are subject to significant dynamic loading. Understanding the nature of this dynamic (cyclic) loading is important for geotechnical experts with responsibility for the soil investigations and the foundation design. Currently, no accepted design method for cyclic loading of piles exists. Therefore, this paper is an attempt to improve mutual understanding of experts in different areas, namely wind turbine loads and foundation engineering. The ultimate goal is to facilitate development of simple, reliable and economic design methods for this area. For this purpose, it is important to clearly identify design situations and the load cases which are the most significant conditions that an offshore wind turbine is exposed to.

When an offshore wind turbine is based on a jacket substructure, the external loads are transmitted into the seabed soil through the jacket piles in form of axial forces. In this paper the characteristics of the axial loads of a jacket pile are presented; similar findings regarding relative load magnitudes (i.e. fatigue loads vs. extreme loads) are also relevant for the design moment of monopile foundations.

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2 Critical axial loads

Firstly, an estimate of a critical cyclic load level is required in order to judge whether certain situations are relevant for the design or not. The axial loading of a jacket pile can be divided in two components: the average load P_{avg} and the cyclic load amplitude P_{cyc}. The cyclic load range is two times the load amplitude.

$$P = P_{avg} + P_{cyc} \tag{1}$$

Both average and cyclic loading are important for pile design. For assessment purposes, the cyclic load and the average load are often expressed as a percentage of the characteristic pile capacity Q_r.

Acc. to [ISO 19902] the axial pile capacity shall satisfy the following condition:

$$P_{d,e} \leq Q_d = Q_r \,/\, \gamma_{R,Pe} \tag{2}$$

where Q_d is the design axial pile capacity, i.e. the design resistance of the pile;

Q_r is the representative[2] value of the axial pile capacity;

$P_{d,e}$ is the design axial action on the pile for extreme conditions;

$\gamma_{R,Pe}$ is the pile partial resistance factor for extreme conditions ($\gamma_{R,Pe}$ = 1,25).

Some methods have been proposed to consider the influence of the cyclic load on axially loaded piles and to determine its critical value. Mittag and Richter [Mittag & Richter, 2005] (among others) have submitted a method to determine the critical amplitude of the cyclic load on piles. Although the approach is limited, it shows the strong dependency of the pile bearing capacity on the cyclic load level and the number of load cycles. The proposed design equation by Mittag and Richter is:

$$\frac{E_{cyc}}{R_c} \leq \kappa \cdot \left(1 - \left(\frac{E_{avg}}{R_c}\right)\right) \tag{3}$$

Using symbols as per [ISO 19902], this equation reads:

$$\frac{P_{cyc}}{Q_r} \leq \kappa \cdot \left(1 - \left(\frac{P_{avg}}{Q_r}\right)\right) \tag{4}$$

In this equation κ is a parameter depending on the number of load cycles und $Q_r = R_c$ is the characteristic pile capacity.

According to this method a stable zone of load combinations can be determined, in which no pile failure under cyclic loading is expected. For a zero average load a cyclic load (load range, i.e. double amplitude) up to 40% of the pile capacity and for an average load of 50% a cyclic

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[2] In [ISO 19902] it is defined that the characteristic value is the main representative value.

load range of 30% is found to be acceptable for $N=10^6$ load cycles. This is in accordance with values stated in other publications. As 50% mean load is a conservative estimate for offshore wind turbines, the critical load range is estimated to be 30% of the characteristic pile capacity as a first approximation.

3 Load cases for wind turbine design

The substructure of an offshore wind turbine undergoes many different loading conditions. The resulting stresses derive from the inner loads of the wind turbine (self weight, rotor rotation, start-up and shut-down loads) and from environmental loads (turbulent wind, stochastic sea state, marine currents, ice, etc.). General information about load cases to be considered for offshore wind turbines can be found in [IEC 61400-3].

Load cases are divided into extreme load cases, which are assessed for ULS (Ultimate Limit State), and fatigue load cases, which are used for FLS (Fatigue Limit State) assessment. The load cases which are considered for FLS assessment are summarized in Table 1.

Description	Design load case (DLC)
Operation (power production)	DLC 1.2
Operation (power production) plus occurrence of fault	DLC 2.4
Start up	DLC 3.1
Normal shut down	DLC 4.1
Emergency shut down	DLC 5.1
Idling turbine	DLC 6.4
Parked and fault conditions	DLC 7.2
Transport, assembly, maintenance and repair	DLC 8.3

Table 1: Load cases for the fatigue design according to IEC 61400-3

Fatigue load cases are evaluated based on the actual site conditions, e.g. by taking the actual wind speed distribution and predicted hours of operation at each wind speed into account. Fatigue loads are then summarized e.g. as load spectra, where load ranges are plotted against accumulated number of load cycles. It is in these spectra that numbers of cycles up to $N_{acc}=10^9$ occur. No partial load safety factors are considered for fatigue loads.

Extreme load cases are evaluated by determining maximum design values occurring, incl. the relevant partial safety factors. Details can be found in [IEC 61400-3].

4 Case study

To illustrate the influence of this set of design situations a case study of a REpower 6M turbine on a jacket substructure with a base width of b=22m in the German North Sea (35m water depth) is presented (Figure 1).

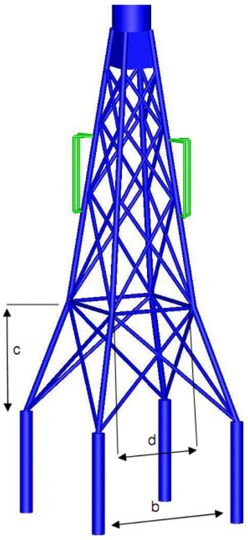

Figure 1: Jacket model

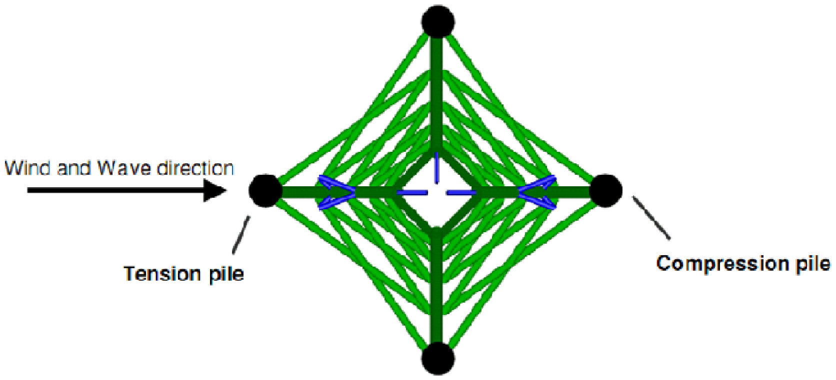

Figure 2: Illustration of tension and compression pile (top view)

Fatigue analysis of relevant load cases was performed for the purpose of the calculation of the axial pile forces. It is assumed here that wind and waves are coming both from the direction shown in Figure 2 as this is the most onerous loading direction for the piles. Therefore the jacket bears the entire moment loading with only two piles; the downwind pile is called the "compression pile", the upwind pile is called the "tension pile" (see Figure 2) as this is the main loading direction from wind and wave loads.

The fatigue loads in the piles were normalized (divided by) factored ULS loads, which correspond to the **required axial design capacity**. Load ranges in the tensile loading region were normalized by the required tensile capacity; the loads in the compressive region (or reversed loads) were normalized by the required compressive capacity. This is conservative compared to normalizing by the characteristic pile capacity (which is larger due to the partial material factor, which is 1.4 acc. to DIN 1054, but only 1.25 acc. to [ISO 19902]).

$$\begin{aligned} \Delta P_{x,tension,norm.} &= \frac{\Delta P_{x,tension}}{\gamma_f \cdot P_{k,tension}} \\ \Delta P_{x,compr.,norm} &= \frac{\Delta P_{x,compr.}}{\gamma_f \cdot P_{k,compr.}} \end{aligned} \tag{5}$$

If the piles are fully utilised, then the required axial design capacity is identical to the design capacity, i.e.

$$\gamma_f \cdot P_{k,e} = P_{d,e} = \frac{Q_r}{\gamma_{R,Pe}} \tag{6}$$

4.1 Statistical evaluation of operating load cases

For the operating load cases the graph of the normalized average pile force and its standard deviation vs. the mean wind speed is shown in Figure 3. Note that wind speed is the most important parameter here because the waves do not have a great impact for a hydrodynamically transparent structure like the jacket.

The following can be seen:

- At low wind speeds between 3m/s und 8m/s the utilization factor, i.e. percentage of required axial design capacity as per Eq. (5) amounts to 15% up to 25% of required compression capacity.
- At a wind speed around 12 m/s the bending moment of the turbine is at its maximum and the pile force attains its maximal value with a utilization factor of 30% (mean value) on the compression side.
- At higher wind speeds (greater than 12 m/s) the mean turbine thrust decreases because the pitch "turns the blades out of the wind" and consequently pile mean loads decrease.
- Mean values are always compressive in this case, tensile loads do only occur with small magnitudes.
- Concerning the standard deviation it can be seen that at high wind speeds close to the cut-out (at 30m/s) the standard deviation is higher compared to lower wind speeds.

So depending on which is the more critical factor for design (average load or load variation) different conclusions would have to be drawn which situation should be investigated further for detailed design. Generally it can be seen that absolute levels and standard deviations during operation are relatively small.

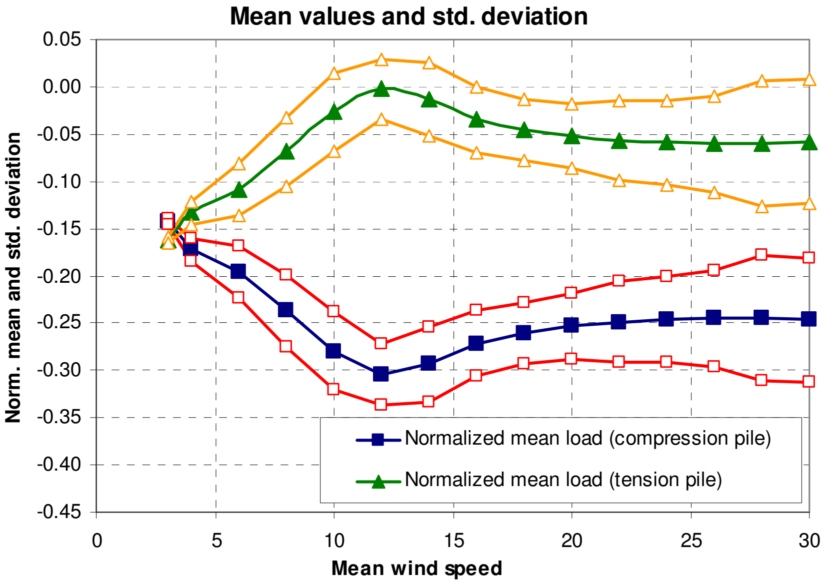

Figure 3: Normalized pile forces (mean ± 2·standard deviation) vs. mean wind speed during operating load cases at different mean wind speeds

4.2 Fatigue load spectra

The load spectrum, showing load ranges vs. accumulated number of load cycles, is a potential basis for the analysis of critical pile loading. The fatigue load spectrum of the normalized force ranges is derived for the compression pile and for the tension pile separately. One challenge when analyzing pile loads is that the loading is of stochastic nature and therefore all possible combinations of average load and load range do occur. Therefore an attempt has been made to make at least some sort of separation of different situations by distinguishing pure tension, pure compression and reversed cyclic loading as shown in Figure 4.

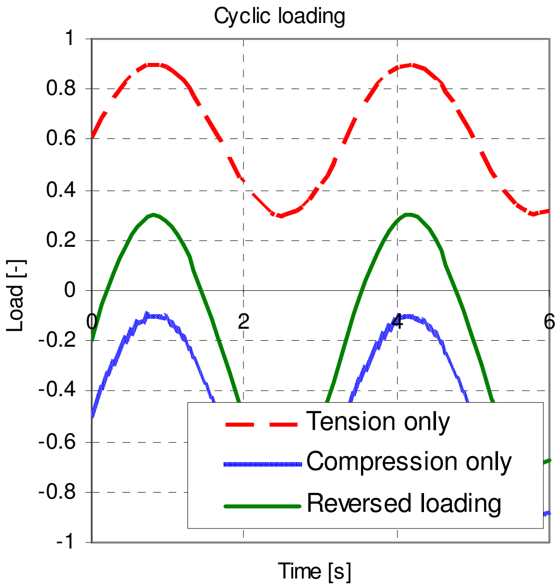

Figure 4: Cyclic loading characteristics

The load spectrum of the axial force range in the compression pile is shown in Figure 5. The following can be seen:

- The pile suffers mostly compression forces and only a few cases of a tensile force and reversed loading. The compression forces in this pile are caused by the normal operation of the wind turbine where the mean load (from dead-weight of the entire installation and the mean turbine load) is sufficiently high to prevent the pile going into tension.
- Rare tension and reversed axial forces are caused by transient events during the service life of the turbine such as emergency stops or fault cases (see Table 1).
- Less than 1000 cycles (out of nearly 10^9 total cycles) are close to or exceeding the critical limit of 30% of required axial design capacity.

Figure 6 shows the load spectrum of the axial force range in the tension pile:

- On this side the pile experiences compression, tension and reversed forces.
- Pure tensile load ranges do only occur with small magnitudes of less than 10% of required axial design capacity.
- Reversed loading does occur, but it is likely that tensile parts of reversed loading is typically small (otherwise pure tensile loading would also occur with larger load ranges).
- Also here, less than 1000 cycles (out of nearly 10^9 total cycles) are close to or exceeding the critical limit of 30% of required axial design capacity.

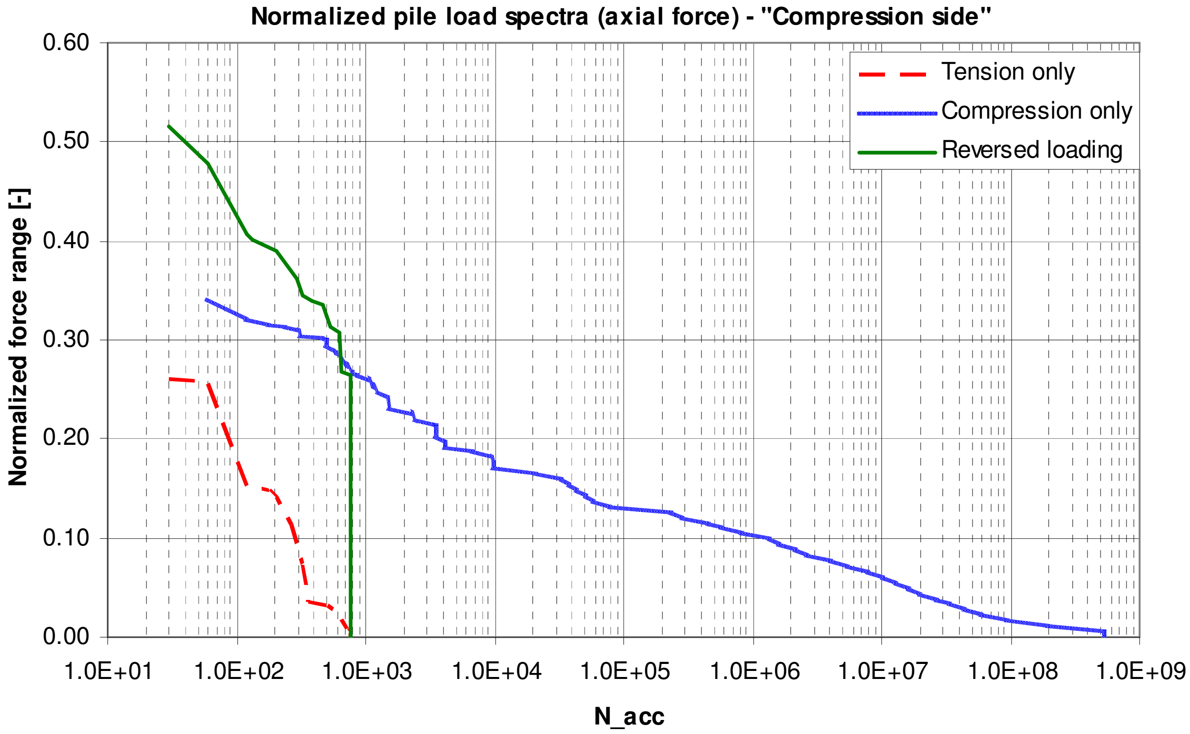

Figure 5: Normalized pile load spectra (axial force) – Compression side

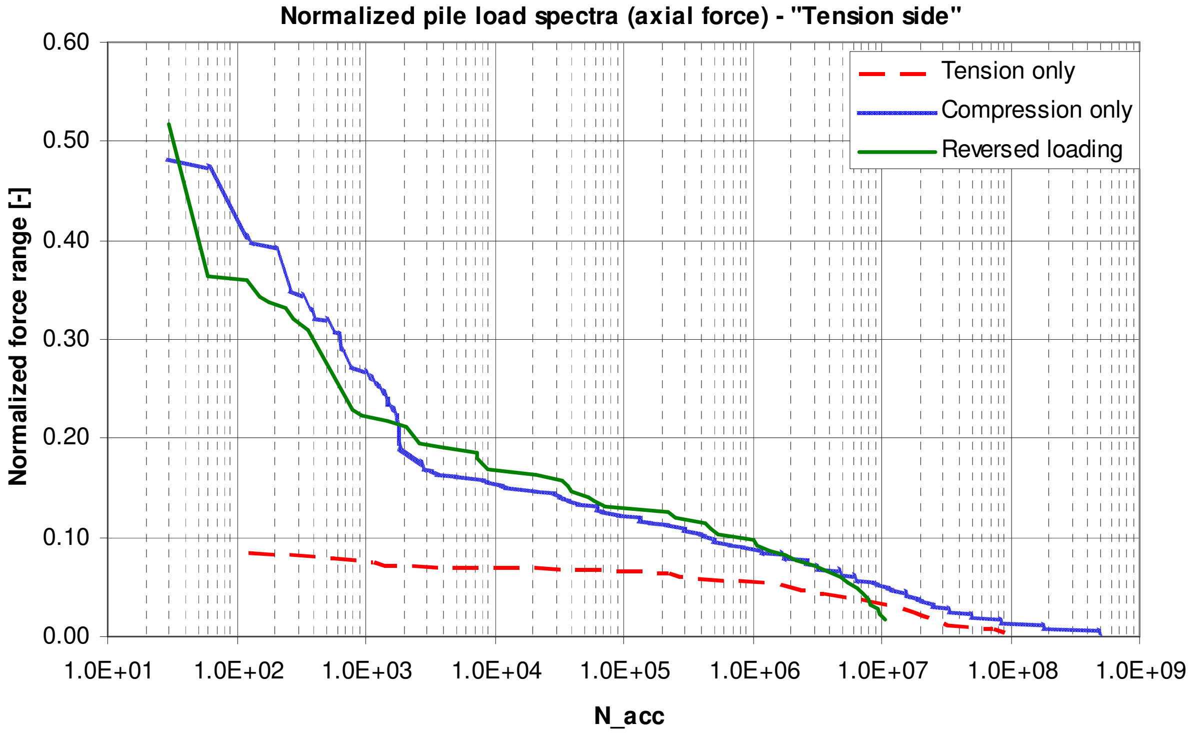

Figure 6: Normalized pile load spectra (axial force) – Tension side

4.3 Load variation during a fault load case

Figure 7 shows the variation of the tower base bending moment during a fault case or an emergency stop in its first 30 seconds. At the beginning of the time series, the tower oscillates with small amplitudes and larger frequencies under normal operation conditions. From the fifth second, the vibration amplitude rises abruptly when a fault situation and/or an emergency stop occurs. As a result, the amplitude of the overturning tower base bending moment increases and dampens out depending on overall structural damping.

The enlarged section of the plot draws attention to the largest tower base bending moment. It can be seen that the loading period is about 3-5s (which corresponds to the first natural eigenperiod of the system). Peaks loads are therefore only present for a very short period of time. It may be relevant for evaluation of cyclic performance that a series of relatively large load ranges occurs during the decay process of the oscillation.

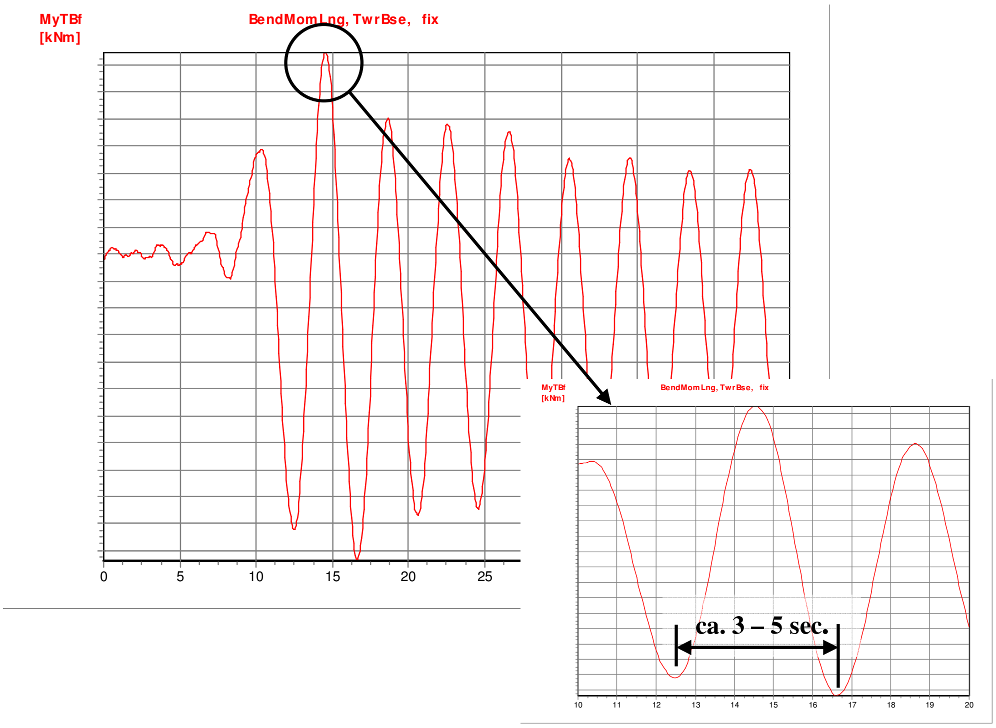

Figure 7: Variation of the base tower bending moment – Fault case or emergency stop

4.4 Load variation and frequencies during operation

Figure 8 plots the variation of the axial pile load in the tension pile as a time series of 600s length when the wind turbine operates around rated wind speed. The pile mean load is largest in this case, leading to a mean load of nearly Zero (indicated by the thick black line) for the tension pile. As show in the picture, the amplitude under this operation condition reaches a maximum 10% of the normalized ULS load.

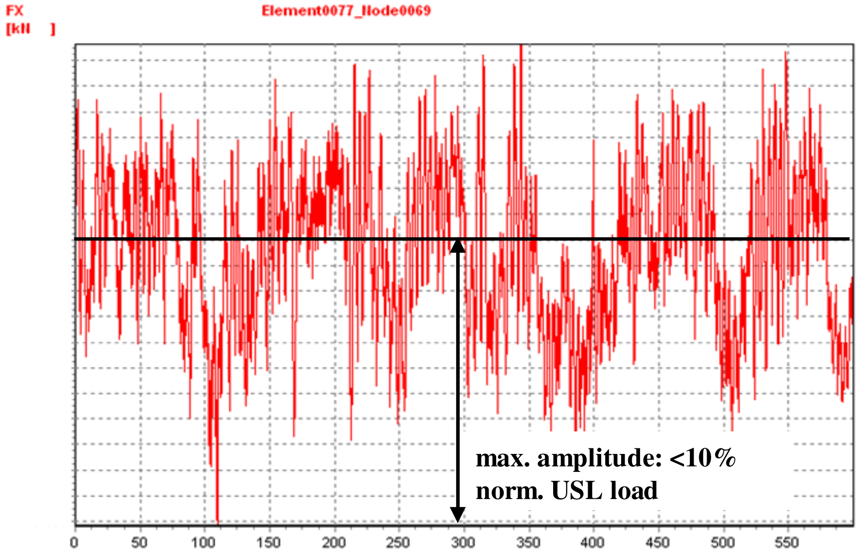

Figure 8: Variation of axial pile load – Operation around rated wind speed

The typical range for the first natural frequency of a wind turbine structure is between 0.20 Hz and 0.35 Hz (i.e. with a period of 3 s to 5 s). The second natural frequency typically lies around 1.5 Hz to 2 Hz. Important loading frequencies are operational frequencies that result for example, from the rotor rotation (1p) and from the passage of the blades through the tower (3p) shadow, among others. In this case study these frequencies are 0.20 Hz and 0.60 Hz respectively for a REpower 6M wind turbine at rated power. The frequencies of the wind turbulence (turbulence models e.g. according to Kaimal) and the marine waves (represented with a JONSWAP spectrum) are low-frequent excitation frequencies.

Figure 9 shows an analysis of the axial pile force in the frequency domain, the governing frequencies during the operation of the wind turbine can by identified from this plot. As it can be seen, frequencies lower than 2 Hz are dominating. The greater peaks between 0 and 0.30 Hz represent the first natural frequency as well as the frequency of the waves and of the rotor rotation. In the same way, the peak around 0.60 Hz constitutes the frequency of the passage of the blades in front of the tower. The third peak around 1.50 Hz corresponds to the second natural frequency of the system.

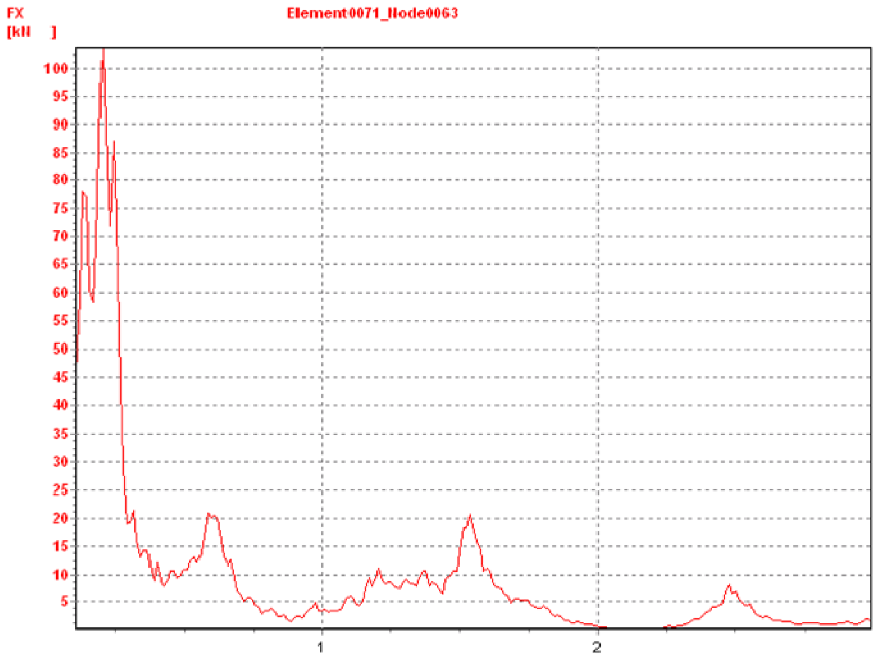

Figure 9: Analysis of operational load case in the frequency domain

4.5 Storm load cases

In Oil&Gas applications, cyclic degradation is only assessed during a storm situation. The critical situation is expected to occur during a storm situation (see Figure 10), where the axial capacity of the pile is reduced due to sustained high loading. Therefore, the storm is modelled with a build-up phase, a peak phase and a reduction phase. Reduction of pile capacity during this storm is checked against the actual loads in all phases.

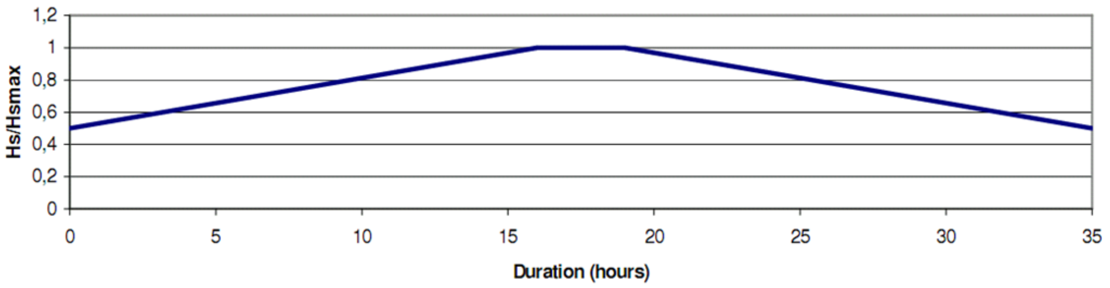

Figure 10: Storm development for evaluation of the degradation of soil's resistance during cyclic action. The peak level is obtained for a sea-state duration of 3 h. Taken from [Norsok N-003]

In Figure 11 a typical time series for the bending moment at tower base for a storm load case is shown. Again, the maximum load occurs with the first natural period, which is about 3s to 5s. This is different to wave loaded Oil&Gas platforms, where the wave period is in the range of 10s to 20s.

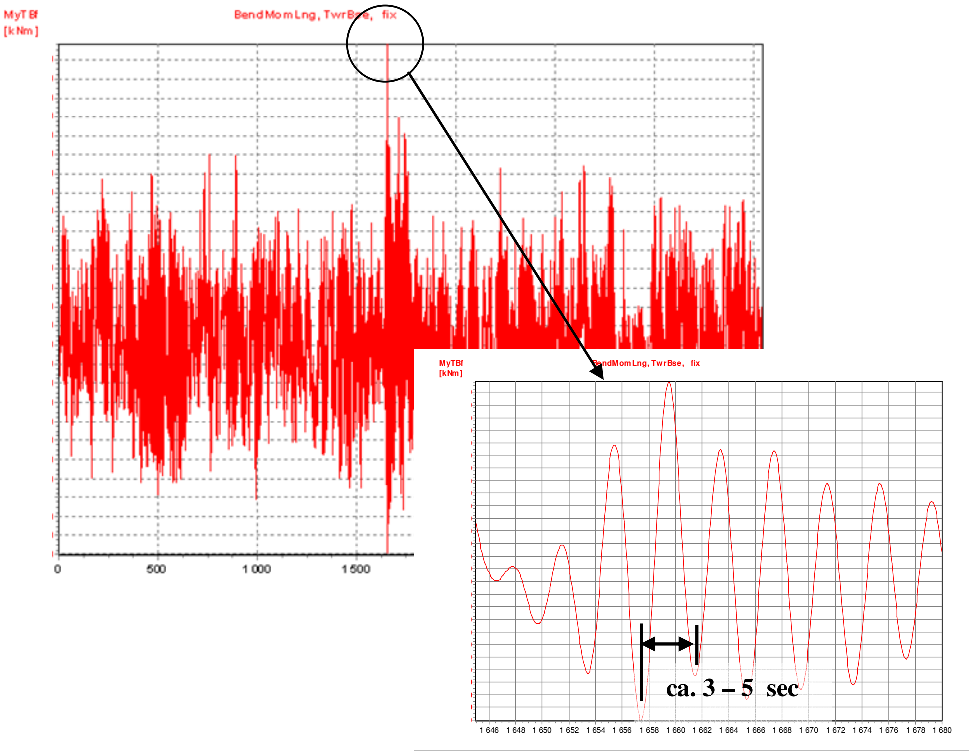

Figure 11: Variation of the base tower bending moment – Storm load case

5 Design situations to distinguish

In accordance with the explanations above, the following design situations can be identified:

- **Cyclic loading during the operation of the turbine:**
  While the turbine is in operation a high number of cycles with low to moderate cyclic load occur (<30% of the required axial design capacity), as shown in the load spectra in Figures 5 and 6.

- **Exceptional loading due to isolated (extreme) events:**
  Isolated events may be emergency stops or fault cases (which are also considered for fatigue assessment and which are included in the fatigue load spectra) or load cases that are normally only considered for ULS design. These load cases have a characteristic load pattern which consists of one large cycle followed by smaller cycles when the vibration dampens out.

- **Cyclic degradation during a storm:**
  Similar to the assessment for Oil&Gas platforms, sustained high (stochastic) loading during a certain period may be critical. Due to the combination of wind & wave loads, plus potential fault scenarios (grid loss), the exact definition of this case is much more complex than for purely wave-loaded structures.

6 Conclusions

The unique loading aspects of offshore wind turbine foundations require further development of the current state of practice in design of these structures. From the example the following conclusions can be drawn for the different limit states to be considered.

Fatigue limit state (FLS):

- For fatigue assessment an exact analysis of fatigue loads (no. of cycles vs. relative amplitude) is crucial.
- The example of this paper indicates that load ranges may be within uncritical (or even beneficial) range for operating conditions. Only a very small fraction of the fatigue loading is within the critical range; critical events are furthermore isolated in time.
- Loading is dominated by low frequencies (<0.5Hz).

Ultimate Limit State (ULS):

- For ULS considerations, load duration is important. The peak loads do only occur for a very short period of time (about 1s to 2s).
- There is no static or quasi-static load. All loads are cyclic and transient. The pile capacity at a certain point in time must be compared to the actual load level.
- Cyclic performance for special events with a series of relatively large cycles must be distinguished from cyclic degradation in a stochastic storm case.

Serviceability Limit State (SLS):

- Accumulated displacements (e.g. inclination of the structure) are important for the operation of the turbine. Therefore prediction of displacements is necessary.
- Additionally, stiffness changes which may lead to changes in natural frequencies may be an issue to consider.

Literature

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