Detecting critical scour developments at monopile foundations under operating conditions

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Abstract

Early warning systems for critical conditions at offshore wind turbines are needed to reduce maintenance costs and avoid catastrophic failures. Monitoring of the critical scour development at monopile foundations is commonly done with cost-intensive scour depth measurements. The scour condition is regarded critical when the depth exceeds the maximum allowed design scour depth during normal operation or due to a severe storm. This practice can lead to high maintenance costs and potentially unnecessary maintenance activities such as refilling of the scour hole or reconstruction of the scour protection. Instead, the exploitation of the structural reserves of fatigue driven monopile foundation designs stemming from design assumption versus real site conditions is suggested. Damage accumulation is highly influenced by the time behaviour of the transient scouring and real soil properties. This paper elaborates on novel low cost monitoring methods to detect when a scour development is truly critical when taking site conditions into account. A combination of fatigue monitoring and natural frequency supervision is proposed for critical scour identification in the framework of an early warning system.

Keywords
Offshore Wind Turbine, Operation and Maintenance, Monopile, Scour, Structural Health Monitoring, Early Warning System, Natural Frequency

1 Introduction

Unscheduled maintenance activities due to unexpected failures are a key driver of Operation and Maintenance (O&M) costs for offshore wind turbines. Increased turbine sizes and the move farther offshore, increase the risk of potentially significant losses of production. Wind farm operators seek to optimize their maintenance strategy by balancing preventive measures, costly scheduled inspections and remote wind farm surveillance. It is well accepted that continuous condition and health monitoring of the wind turbine could greatly contribute to the mitigation of operational and financial risks related to O&M. In practice, such an early warning system has to fulfil a number of requirements: be failure mode specific, assess the level of degradation or severity of failure, produce reliable alarms that are easy to understand and ideally operate in an automated mode.

This paper addresses unexpected scour development at monopile foundations as a consequence of extreme events, strong currents as well as failures of scour protection as
documented in [1] and [2]. Monopiles are the most commonly used support structures used for current European offshore wind projects [3]. Scour is a serious hazard for monopiles, as it can cause a loss of stability. Furthermore the flexibility of the structure increases with this effect. Recent scour research has focused on the prediction of scour development and design of scour protection measures. The remaining uncertainties in predictions for scouring within tidal environments [2] and the substantial costs and susceptibility to failure of scour protection [1] call for continuous monitoring.

In section 2 the suitability of different scour indicators are assessed analytically. Section 3 describes the detailed analysis conducted with structural response calculations for different scenarios. As a result, the suitability of natural frequency monitoring as a critical scour depth indicator is discussed in section 4. Section 5 includes the motivation of monitoring fatigue for scour detection and refers to recently developed load monitoring approaches. The final conclusions are given in section 6.

2 Analytical assessment of scour indicators

From a design perspective, a condition is regarded critical where the structure is prone to loading that exceeds the design resistance, defined by limit states: ultimate (ULS), fatigue (FLS) and serviceability (SLS). Hence, the critical scour depth is a state where due to scouring one of these three limit states is violated. Violation of limit states leads to yielding, fracturing and the loss of the global stability.

Ideally, an indicator value for critical scouring directly reflects the closeness to the limit state that the support structure was designed for. An alarm is raised when the chosen threshold is exceeded. Due to the complexity of the damage mechanisms linked to scour and the consequently changed static and dynamic behaviour of the structure as well as financial and technical limitations of measurement principles, indicators for critical scour depth are indirect. For example, measuring the scour depth (indicator), allows detection of when the design scour depth (threshold) is exceeded. But only in the absence of structural reserves will this lead to a critical condition of the support structure, as defined by the limit state formulations. For optimal maintenance decisions, further information is required to truly assess the criticality.

These considerations lead to desired properties for a critical scour indicator that can be summarized in three categories:

- Criticality
- Measurability
- Uniqueness

Criticality means that the indicator value for critical scouring relates to all affected limit states as directly as possible. For example, the tilt of the pile as SLS can be directly monitored with low cost inclinometers but is not sufficient as an indicator for critical scour depth.

Measurability means that cost-effective and reliable measurement techniques for the indicator exist, delivering acceptable data quality in a robust and maintenance free manner. For example, the FLS of one spot can be directly monitored with strain gauges but the technology lacks robustness in the offshore environment.

Uniqueness of the indicator to describe scour is crucial to allow for root cause detection and enable target-orientated maintenance. For example, a change in the global natural frequency does not necessarily relate to a changed scour depth.

Below, the suitability of the scour depth, the global natural frequency as well as tilting and fatigue variables as indicator values are discussed in view of the above defined criteria. Table 1 gives an overview of the indicators, their ability to identify a critical state, known thresholds, possible detection methods and their uniqueness in detecting scour.

The scour depth $S$, which is the deviation of the standard mudline level around the monopile, is not directly linked with any failure or
serviceability limit state. A common criterion for the allowed scour depth relates to the pile diameter at mudline $D$ and can be estimated according to design guidelines ($S < 1.3D$ [4]). There are several approaches to measure the scour depth directly via optical methods or float-out devices. No other effect besides scouring or seabed movement is known to affect the scour depth.

The first global natural frequency $f_0$ will decrease due to increased scouring, leading to changed fatigue life consumption (linked to FLS) and unfavourable resonance effects. There are no universal upper or lower bounds defined for $f_0$, but the frequency should not coincide with excitation frequencies. Germanischer Lloyd recommends in its guideline [5] that the ratio of a rotor-induced excitation to one of the natural frequencies of the tower shall not be between 0.95 and 1.05. Natural frequencies can be assessed by measuring accelerations and performing modal analysis [6]. $f_0$ is affected by any stiffness or mass change of the system, e.g. more mass due to marine growth, less mass and stiffness due to corrosion, more or less oscillating added water mass due to changing water levels or a stiffness reduction as result of soil degradation. Furthermore, stiffness changes may occur in a grouted connection, as result of cracks or other structural effects.

The pile head rotation at mudline $\varphi_{\text{head}}$ increases with increasing scour and is directly linked with the SLS. The criterion $\varphi_{\text{head}} < 0.25^\circ$ for the permanent accumulated rotation is listed as an example in the DNV guideline [4] as a serviceability criterion and is usually defined by the turbine manufacturer. Measurement of the non-permanent rotation can provide an indication for the loss of equilibrium and violation of the ultimate limit state. The pile rotation may be measured by an inclinometer at mudline. Similar criteria for the overturning risk as the loss of vertical tangent, zero-toe-kick and maximal displacement at mudline [5] are harder to measure. Soil degradation and the load intensity can affect the pile tilt besides scouring.

Fatigue damage as a result of accumulated cyclic loading changes as the scour hole affects the global natural frequency. The stress cycles adding up to a Damage Equivalent Load (DEL) at selected hot spots can be directly measured with strain gauges and subsequent rainflow counting. The DEL relate to the fatigue limit state via the material S-N curve. The DEL is insufficient for the detection of critical scouring as a number of environmental and operational parameters have an impact on the cyclic loading.

To sum up, none of the presented values is solely capable of satisfying all requirements set out for a critical scour indicator.

## 3 Simulation study

The effects of scouring on the limit states are manifold. As argued above, a scour indicator cannot be based on a single measurement but requires a combination of different favourable

<table>
<thead>
<tr>
<th>Indicator</th>
<th>Criticality</th>
<th>Threshold</th>
<th>Measurability</th>
<th>Uniqueness</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S$</td>
<td>None</td>
<td>$1.3D$ (design)</td>
<td>Sonar, radar, float-out devices</td>
<td>Yes</td>
</tr>
<tr>
<td>$f_0$</td>
<td>Resonance (fatigue)</td>
<td>±5% of 1P, 3P</td>
<td>Accelerometers and modal analysis</td>
<td>Marine growth, corrosion, water level, soil degradation, grout...</td>
</tr>
<tr>
<td>$\varphi_{\text{head}}$</td>
<td>Overturning</td>
<td>$0.25^\circ$ (design)</td>
<td>Inclinometer at mudline</td>
<td>Load intensity, soil degradation</td>
</tr>
<tr>
<td>DEL</td>
<td>Fatigue</td>
<td>S-N curve</td>
<td>Strain gauges, accelerometers</td>
<td>Load composition, various</td>
</tr>
</tbody>
</table>

Table 1: Possible scour indicators
monitoring approaches that relate directly to the limit state formulations of the design. To assess the structural response under scouring quantitatively, detailed load and natural frequency calculations are performed as described below.

The software used for the simulation study is Ramboll Offshore Structure Analysis Programs (ROSAP), a tool package of programs to design and optimize offshore structures. The core of ROSAP is a finite-element-based program for static and dynamic analysis of spatial frames, truss structures and piping systems. The support structure and the rotor-nacelle assembly are modelled in ROSAP as masses, moments of inertia and eccentricities. Elements are defined as Timoshenko beams considering shear deformations. The soil resistance and stiffness are implemented as a non-linear spring model according to American Petroleum Institute’s standard for designing of offshore structures [7]. Natural frequency calculations consider added water masses for all structural parts. Marine growth and corrosion can be implemented and evaluated.

A sensitivity study of the natural frequency is conducted with the Natural Frequency Analysis (NFA) tool of ROSAP, in order to evaluate the impact of other environmental parameters on global natural frequency then the scour. A baseline scenario is defined for scour depth, marine growth, corrosion and water level. These parameters are individually varied up to extreme values.

The impact of scour is evaluated with ULS, FLS, SLS and NFA checks with concept study detail according to current guidelines. In the scope of this research work, distributed hydrodynamic loads are combined with concentrated loads from the wind turbine for ultimate and fatigue loading calculations. Different scour depths are investigated.

The design fatigue uncertainty is evaluated by reruns of FLS simulations with varied settings.

A monopile design of an up-to-date project with a large turbine with >5 MW power and a deep water site is used for this research (Design I). Additionally, validations have been done for ULS, FLS, SLS and NFA calculations for a second realistic monopile design (Design II) with a different specific water depth and mounted turbine type.

4 Natural frequency as scour indicator

The NFA calculations confirm the correlation between natural frequency and developing scour. In Figure 1 the normalized values of the first global natural frequency against normalized scour depth are visualized for designs I and II. Selected results of other natural frequency calculations for scour at monopiles from [8], [9] and [10] are added. The frequency reduction by scouring is of distinctly different sizes for different designs.
The impact of different environmental effects on the natural frequency is investigated and the according results are given in Table 2. The natural frequency reduction by scour is distinctly stronger than for corrosion, water level changes or marine growth. All minor effects together reduce the natural frequency in the order of only one eighth of the scour impact. In addition, a second limited sensitivity study for a design variant confirms the order of the impacts, although the specific values differ.

The correlation of scour and the natural frequency can be used to define a look-up table for identifying scour. Measured natural frequencies can be easily transformed to scour depths, if the function is known for the specific design.

Coinciding scour, corrosion and water level variations are investigated. Lifetime corrosion allowances (0.3 mm/a external, internal 1 mm) and 50 year extreme water levels are combined with scour states from 0 to 1.3 $D$ in a factorial investigation. A linear interpolation between the natural frequency look-up values is assumed for the determination of scour depths. The resulting look-up error due to unknown corrosion and water level states is visualized in Figure 2. The determination of scour depth from frequency measurements can deviate by more than 0.2 $D$ in the flat part of the frequency curve near the reference. However, the error is smaller for the more critical larger scour depths where the frequency curve is steeper. The look-up table monitoring approach is mostly conservative with scour depths greater than the real scour depth if other effects interfere.

The results of ULS, FLS, SLS, and NFA calculations with different scour depths give

![Figure 1: Natural frequency dependency on scour for different designs. Frequency normalized to the reference frequency, scour depth $S$ normalized to the monopile diameter $D$ and given per unit (pu)](image)

<table>
<thead>
<tr>
<th>Effect</th>
<th>Parameter limit</th>
<th>Frequency change</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scour</td>
<td>$S/D = 1.3$</td>
<td>−5.04 %</td>
</tr>
<tr>
<td>Corrosion</td>
<td>Lifetime (0.3 mm/a extern and 0.15 mm/a intern)</td>
<td>−0.49 %</td>
</tr>
<tr>
<td>Corrosion (intern restricted)</td>
<td>As above, intern ≤1 mm</td>
<td>−0.37 %</td>
</tr>
<tr>
<td>Positive water level change</td>
<td>Upper splash zone border</td>
<td>−0.18 %</td>
</tr>
<tr>
<td>Marine growth</td>
<td>Basic GL [5] recommendation</td>
<td>−0.03 %</td>
</tr>
<tr>
<td>Negative water level change</td>
<td>Lower splash zone border</td>
<td>+0.14 %</td>
</tr>
</tbody>
</table>

Table 2: Global natural frequency changes for extreme variations of environmental parameters
information about the criticality of the natural frequency. In Table 3 the limits of tolerable scour depths are given for the two investigated designs. The support structure designs are fatigue driven and any scour results in an unacceptable fatigue lifetime reduction. The natural frequency change is not the most critical consequence for these designs, but fatigue is dependent on the natural frequency. The specific scour depth limits according to NFA, ULS and SLS checks vary up to 0.4 \( D \) for the two designs.

All in all, the measurability and uniqueness of the natural frequency are seen as appropriate, but the direct links to the limit state formulations are missing.

### 5 Fatigue monitoring

#### 5.1 Motivation

If amongst the limit state formulations during design, fatigue is the limit state with the least reserves under scouring, a monitoring of the cyclic loading is required to continuously determine the level of criticality. Several assumptions or simplifications in the site specific fatigue load calculation may even lead to a compensation of fatigue damage caused by scouring.

The main parameters that influence the fatigue loads and damage calculation are listed in Table 4 and grouped in five categories. Systematic assumptions are in accordance with the procedures described in the design guidelines. Parameters like the Design Fatigue Factor of 3

![Figure 2: Uncertainty in scour depth look-up from natural frequencies due to unknown corrosion state and water levels, marked as grey area. Natural frequencies normalized to reference, scour depth \( S \) normalized to pile diameter \( D \) and given per unit (pu).](image)

<table>
<thead>
<tr>
<th>Limit state calculation</th>
<th>Scour limit, design I</th>
<th>Scour limit, design II</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fatigue Limit State</td>
<td>( S = 0 )</td>
<td>( S = 0 )</td>
</tr>
<tr>
<td>Natural Frequency Analysis</td>
<td>( S \leq 0.5D )</td>
<td>( S &lt; 0.9D )</td>
</tr>
<tr>
<td>Ultimate Limit State</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pile displacement</td>
<td>( S &lt; 0.6D )</td>
<td>( S \leq 0.6D )</td>
</tr>
<tr>
<td>Steel utilization</td>
<td>( S \leq 1.0D )</td>
<td>( S \leq 0.7D )</td>
</tr>
<tr>
<td>Soil stability</td>
<td>( S \leq 1.1D )</td>
<td>( S \leq 0.8D )</td>
</tr>
<tr>
<td>Serviceability Limit State</td>
<td>( S \leq 1.2D )</td>
<td>( S \leq 1.6D )</td>
</tr>
</tbody>
</table>

Table 3: Tolerable scour depths according to different limit states for two investigated modern monopile designs. Scour depth \( S \) normalized to the pile diameter \( D \).
are commonly used to introduce desired conservatism in design, but could be omitted when determining the site specific loading with measurements. The design category collects specific material characteristics or design choices for the calculation as e.g. the specific S-N curve. The categories loads and environment include the used wind or wave characteristics and the environmental boundaries as e.g. scour.

To assess the impact of selected parameters on the fatigue damage accumulation, a selection of the listed parameters is varied in a FLS sensitivity study. The parameters are changed in small steps, using realistic value ranges where possible. Figure 3 shows the resulting fatigue damage of the studied variations.

A reduced water level is investigated by an implementation of a less conservative global water level rise. The marginal water level reduction of 0.3 m could already compensate a slight scour with a depth of $S/D = 0.15$. Load equivalent turbulence intensities are provided by the turbine manufacturer for a park configuration, which is used in the reference, or for IEC class B turbulence intensity. The damage per year due to wind loads at approx. 0.025 higher turbulence intensity is nearly as high as the one with an extreme scour depth ($S = 0.5D$). The equivalent wind loads are defined for a site-specific average mean speed. A variation of this assumed mean speed by approx. ±0.5 m/s results in a damage change larger than in the case of slight scour. An increase of structural damping by 0.1 percentage points results in a damage reduction of a similar magnitude.

### Table 4: Parameters influencing the design Fatigue Limit State (FLS) calculation

<table>
<thead>
<tr>
<th>Category</th>
<th>Parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Systematic</td>
<td>Turbine and soil model, Sea state simulation by spectrum, Rainflow counting, Palmgren-Miner rule (linear damage accumulation), Design Fatigue Factor (DFF) / material factor, Stress Concentration Factors (SCF)</td>
</tr>
<tr>
<td>Design</td>
<td>S-N curves, Damping, Pile driving damage</td>
</tr>
<tr>
<td>Loads</td>
<td>Mean wind speed and directional distribution, Wave characteristics, Misalignment of wind and waves, Turbine non-availability time</td>
</tr>
<tr>
<td>Environment</td>
<td>Scour, Water level, Corrosion, Marine growth</td>
</tr>
</tbody>
</table>

![Figure 3: Yearly fatigue damage for selected parameter variations](image-url)
The sensitivity assessment of design parameters on FLS is idealised and highly dependent on the final structural design and site specific conditions. The study highlights qualitative changes in the resulting fatigue damage, nevertheless. The impact of the stochastic variables on fatigue damage is sufficiently high to justify the fatigue monitoring technique as a method to monitor FLS thresholds in cases of fatigue driven designs.

5.2 Realisation

Application of strain or acceleration sensors below sea level or even below mudline may provide sufficient loading data for a monitoring of fatigue. Continuous and long-term operation of these sensors could be very costly with respect to the maintenance effort. However, more cost-efficient load monitoring approaches have been developed recently by [11], [12] and [13].

If continuous load measurements or estimations are available, stress cycles can be counted to generate a parameter similar to the design process. With the Palmgren-Miner rule damage can be estimated and compared with the corresponding design damage.

Fatigue monitoring can additionally contribute to the opportunity of lifetime extension. This may be reasonable in the opposite case, if the real damage is smaller than the assumed damage calculated in the design.

Fatigue monitoring is linked with the dynamic failure caused by scour for fatigue driven designs. Dynamic load measurement and estimation have been investigated in research projects recently and an adequate measurability with low costs is presumed. Uniqueness for detecting critical scour is not given at all for fatigue monitoring.

6 Conclusions

The suitability of different methods for critical scour monitoring is assessed at two example fatigue driven support structure designs. A global natural frequency look-up approach is found reasonable to monitor critical conditions due to scouring with respect to ULS and SLS. The accuracy of scour depth prediction is good despite the presence of other frequency changing effects. The check on the defined criteria – criticality, measurability, uniqueness – on a scour indicator reveals a lack of a direct link to FLS.

The FLS calculation is based on a number of parameters that lead to conservatism. Different over- or underestimated effects may compensate each other when monitoring fatigue loads at the site. A sensitivity study revealed that fatigue monitoring is suitable to detect structural reserves and allow for temporarily deeper scour depth than the design scour depth without the need for maintenance activities.

A combination of fatigue monitoring and natural frequency supervision is suggested for the detection of critical scour conditions in the sense of ULS, FLS and SLS. However, in order to establish an early warning system using effective thresholds for natural frequency changes and yearly damage accumulation the design conditions of the support structure have to be known.

Future research may focus on the implementation of the suggested combined measurement strategy to check the measurability criterion in more detail. According to in-house experience, fatigue or natural frequency limits are most likely to be driving for upcoming designs of monopile substructures. If extreme loads are decisive, the supposed method will not succeed and other approaches will have to be investigated.

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