A Simplified Approach to Wave Loading for Fatigue Damage Analysis of Monotowers

Paul E. Thomassen (NTNU) and Jørgen Krokstad (Statkraft)
paul.thomassen@ntnu.no jorgen.krokstad@statkraft.no

Introduction

The monopile is the dominating substructure concept used for offshore wind turbines. Offshore wind farms have so far been built at a depth of up to 24m. As the importance of wave loads increase when deeper waters (30-60m) are considered for wind farms, it becomes increasingly important to correctly and efficiently include wave loading in structural analysis. Also, for deeper waters monopiles are expected to gradually become less economical compared to alternative substructure concepts (e.g. truss towers), and wave loading is important to rate different alternatives.

For several reasons it is of interest to make a simplified evaluation of the wave climate and the accompanying wave forces, e.g.:

• Wind turbine substructure concepts can be evaluated directly connected to a specific site can be useful in design of a real structure. However, wind loading is ignored to allow a broader discussion of wave loading. Likewise, dynamic effects are ignored.

• Using a simplified method gives an improved understanding of the nature and influence of wave climate and loading.

• A simplified method is necessary due to the computational effort in the context of fatigue loading.

• In situ wave measurements in particular, but also computer simulations are resource demanding. Thus, a simplified approach is very useful in an initial phase of a project.

• A scatter diagram based on a limited number of key parameters that is both easy to construct and not directly connected to a specific site can be useful in structural design as a (partial) description of the wave climate.

The Keulgan-Carpenter KC number and the slenderness relationship are typically used to classify wave loading on a vertical bottom mounted cylinder. As the KC number is small, drag can be neglected and the mudline moment amplitude can be found analytically by integrating the wave load over the depth:

\[ M_{\text{wave}} = \frac{\rho g D^2 \pi H^2}{8} \left( 1 - e^{-\frac{D}{2H}} - 2 e^{-\frac{D}{4H}} \right) \]

The structure is assumed to be quasi-static and each seastate is assumed to consist of regular waves with wave height \( H \) and period \( T = T_p \).

As regular waves are assumed, the stress history of a seastate will be sinusoidal with the period of the waves. The critical fatigue detail is assumed to be located at the mudline cross-section. SN curve G is assumed to get reasonable values for fatigue life.

A rational and efficient approach to constructing a scatter diagram based on SMB curves, fetch, the effect of shallow water, the duration of winds, and wind distribution is presented. The approach is recommended for use both in addition to and in the absence of more resource demanding alternatives.

The fatigue limit state is generally assumed to be very important for offshore wind turbines. Here, wave loading on a monopile is discussed in the context of fatigue loading.

Typically, wind loading will dominate over wave loading, and must, of course, be taken into account in design of a real structure. However, wind loading is ignored to allow a broader discussion of wave loading. Likewise, dynamic effects are ignored.

A (Rational) Scatter Diagram

<table>
<thead>
<tr>
<th>SMB curve</th>
<th>Fetch 50km / 500km</th>
<th>Scattering diagram</th>
</tr>
</thead>
<tbody>
<tr>
<td>E.g. Carter (1982):</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Duration limited:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( H_s = 0.0146D^{0.5}U_{10}^{0.4} )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( T_p = 0.540D^{0.7}U_{10}^{0.7} )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fetch limited:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( H_s = 0.0163F[km]^{0.5}U_{10}^{1.3} )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( T_p = 0.566F[km]^{0.3}U_{10}^{1.2} )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fully developed:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( H_s = 0.0163F[km]^{0.5}U_{10}^{1.3} )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( T_p = 0.566F[km]^{0.3}U_{10}^{1.2} )</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Fatigue Life at Mudline

<table>
<thead>
<tr>
<th>Fetch/Depth</th>
<th>Fatigue life at mudline</th>
</tr>
</thead>
<tbody>
<tr>
<td>50 km: 81/7 year</td>
<td>37 year</td>
</tr>
<tr>
<td>500 km: 239 year</td>
<td>6 year</td>
</tr>
</tbody>
</table>

Wind Distribution

- Weibull (2-param.): Shape: 1.9, scale: 10.0
- 50-year: 35 m/s
- 1-year: 28 m/s
- \( U_{10,\text{mean}} = 8.9 \text{ m/s} \)

Wave Loads

- Scatter diagram
- Monopiler: \( D = 6 \text{ m}, t = 60 \text{ mm} \)
- Potential theory
- Keulgan-Carpenter: \( \frac{K}{D} = 2.5 \%
- Morison's eq.
- \( \lambda = 1.3 \)
- Slenderness
- Wind load on a vertical bottom mounted cylinder.
- Effect of shallow water
- \( U_{30\text{m}} = 7.5 \text{ m/s} - 22.5 \text{ m/s} \)

Fatigue Damage

- Scattering diagram and Wave spectrum
- Monopiler (OC 3 baseline) \( D = 6 \text{ m}, t = 60 \text{ mm} \)
- SN-curve: \( G \)
- Wave loads at mudline
- Time domain analysis for each seastate
- DNV (2005)

Conclusions

- The fatigue damage of the monopile at the mud line has been found considering only wave loads. The minimum fatigue life for 30m and 50m depth was 239 year and 8 year, respectively. When wind loads are also included wave loads are expected to be important due to the exponential nature of fatigue damage.

STATKRAFT OCEAN ENERGY RESEARCH PROGRAM