Pile-driving analyses of monopiles with pre-installed flanges

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Tim Oliver Janele
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Agenda

- Introduction – Flanged Monopile Connections
- Pile-Driving Analyses
- Flange Loading during Driving
- Concluding Remarks
Grouted connection
- Overlap between TP and MP filled with high-density concrete
- Sophisticated installation with restricted weather window

Bolted flange connection
- Steel-to-steel connection with bolted flanges
- **Pile-Driving on MP-Flange**
Pile-Driving on Flanges

Steel-to-steel impact
Ram → Anvil → Flange
30 blows/min, 3000 kJ, 200 MN impact force

Driving-proof flange design
Inclination towards inside
Load transfer through outer flange
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Pile-Driving Analyses – Driveability Study

Wave Equation Analysis
Stress wave propagation (1D Wave Equation)

\[ \frac{\partial^2 w}{\partial t^2} = c^2 \frac{\partial^2 w}{\partial z^2} \]

\[ c = \sqrt{\frac{E}{\rho}} \approx 5200 \frac{m}{s} \]

Soil resistance
- Spring-Damper model with in-situ soil parameters (CPT)

Outcome:
- Blow-Count (blows/penetration depth)
- Axial stresses
Pile-Driving Analyses – Detailed Finite Element Model

Transient dynamic FE Analysis

Validation of FE-Model against Wave Equation Analysis

LS-DYNA keyword deck by LS-PrePost
Time = 0
Contours of Z-stress
min=0, at elem# 1
max=0, at elem# 1
max displacement factor=100

Impact force (pile head)
Settlement (pile toe)
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Flange Loading – Hot Spots

(1) Flange surface
- Local plastification at contact edge
- ‘Polished ring’ visible on-side

(2) Flange neck
- Stress wave propagation through ‘bottleneck’
- High stress utilization
Flange Loading – Initiation of Oscillation

**Vertical oscillation**
- Frequency as function of pile length and speed of sound $c$
- Affected by soil damping and additional hammer restrikes

**Bending oscillation**

Alternate loading at the flange neck
Flange Loading – Driving induced Fatigue Damage

Cumulated damage

\[ D = \sum D_i \cdot n_i \approx 0.3 \ldots 0.4 \]

- \( n_i \) (number of strikes)

- \( D_i \) (individual damage)

- \( n_i \) (number of strikes)

- \( D = \sum D_i \cdot n_i \approx 0.3 \ldots 0.4 \)

- 30 - 40 % reduction of fatigue strength during pile-driving

- Mitigating measures
  - Increased wall thickness: \( \Delta t = 5\text{mm} \) \( \Rightarrow \) -15 % operational damage
  - Reduced impact energy: \( 0.75 \cdot E_{\text{Hammer}} \) \( \Rightarrow \) -10 % driving damage
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Concluding Remarks

Impact driving on flanges is well feasible, but requires:

– Accurate prediction of pile-driving loads

– Highest accuracy in manufacturing + testing

– Offshore: High precision in driving and quality assurance
Thank you for your attention!

Tim Oliver Janele
tim-oliver.janele@dnvgl.com
+49 4036149 8654

www.dnvgl.com

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**App. 01 Optimized flange geometry – Design Driver**

**Flange inclination (g)**

Compromise
- Increase g to ensure that loads are only transferred through the defined contact area
- Minimize g to ease offshore installation (gap of MP-TP flange connection closed by tightening of bolts / shim plates)

**Contact width (c)**

Major influence on load distribution
- Larger c: Increase of downwards bending
- Smaller c: Increase of upwards bending

**Flange neck (a/b)**

- Elliptical shape to soften the ‘bottle neck’
  (a/b = 0.5 results in a stress decrease of up to 10% compared to a circular shape)
App. 02 Misalignments/Tolerances

**Misalignments of the hammer-pile configuration**

- A vertically driven monopile is ensured by a positioning system which adjusts the verticality during the early driving phase. Driving at high energy is only performed once the pile reaches a stable vertical position.
- The hammer sleeve fixates the hammer upon the monopile. Therefore, misalignments between anvil and flange top are neglected.

**Flatness tolerances of the anvil-flange contact**

- Flange and anvil: Manufacturing tolerances $<< 1 \text{ mm}$
  Considered by modelling of sinus shaped contact surface

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Confirmation of anvil/flange manufacturing tolerances by measuring

Inspection of the anvil (wear effects) before each installation