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Pile-driving analyses of monopiles with pre-installed flanges

Offshore Wind R&D Conference 2015

Bremerhaven

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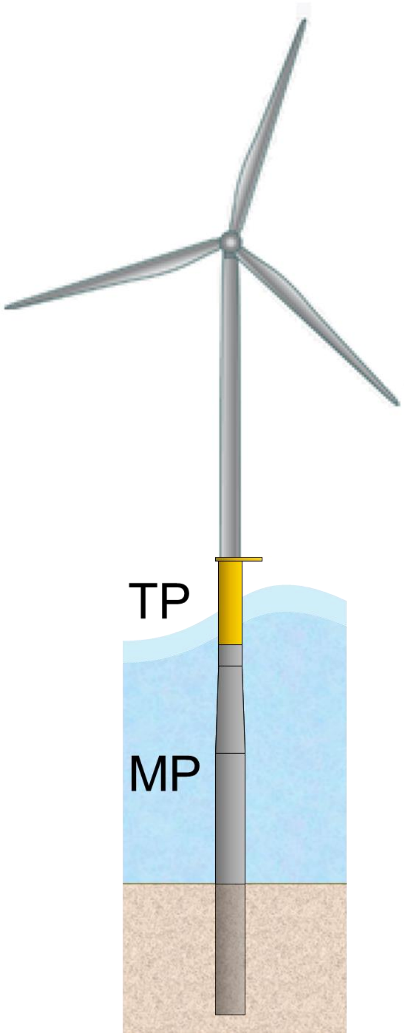
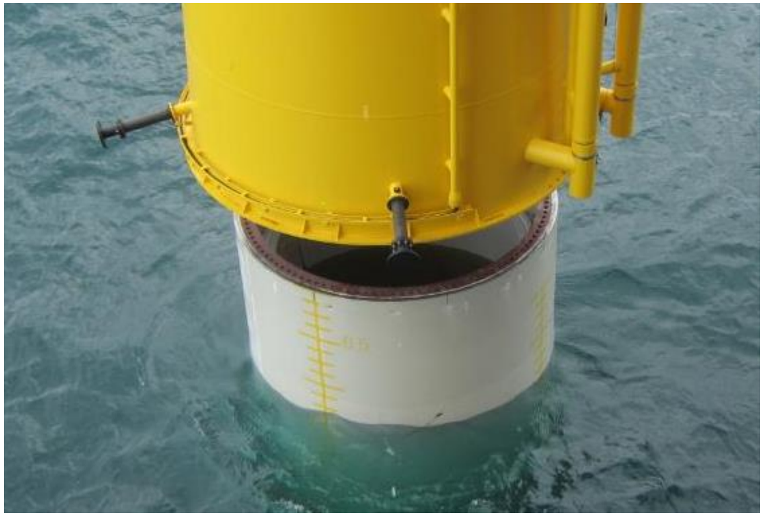
Agenda

- Introduction – Flanged Monopile Connections
- Pile-Driving Analyses
- Flange Loading during Driving
- Concluding Remarks

Monopile Foundations – Grouted vs. Bolted Connection



Grouted Connection *Dan Tysk, www.dantysk.vattenfall.de*



Bolted Connection *Sandbank, www.blog.vattenfall.de*

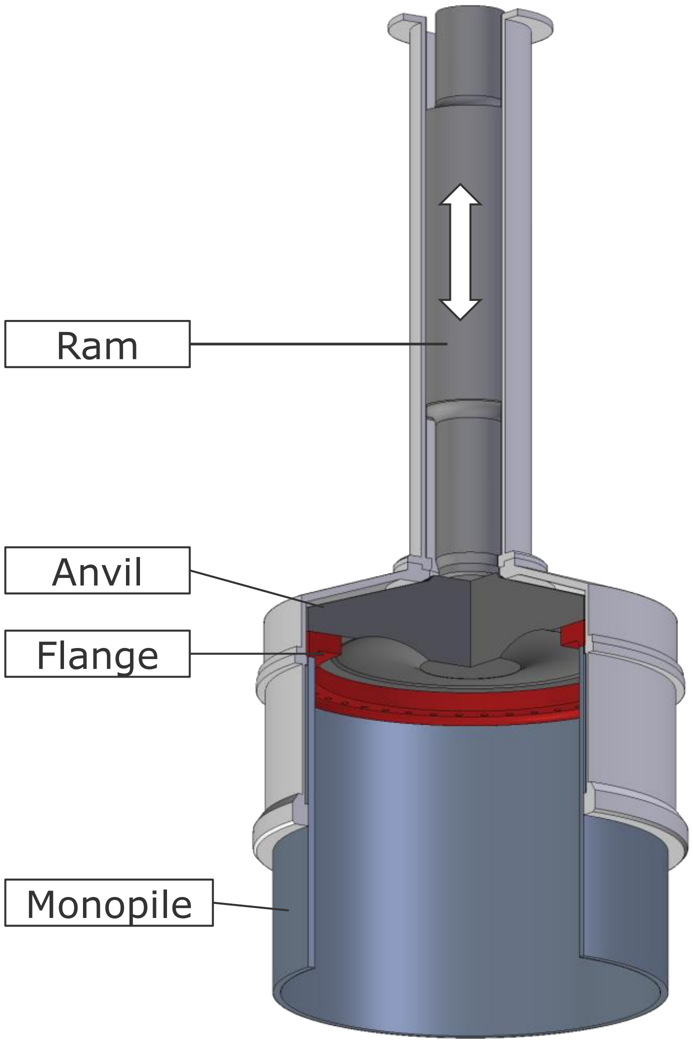
Grouted connection

- 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



Hydraulic Hammer - Driving Configuration

<u>Steel-to-steel impact</u>

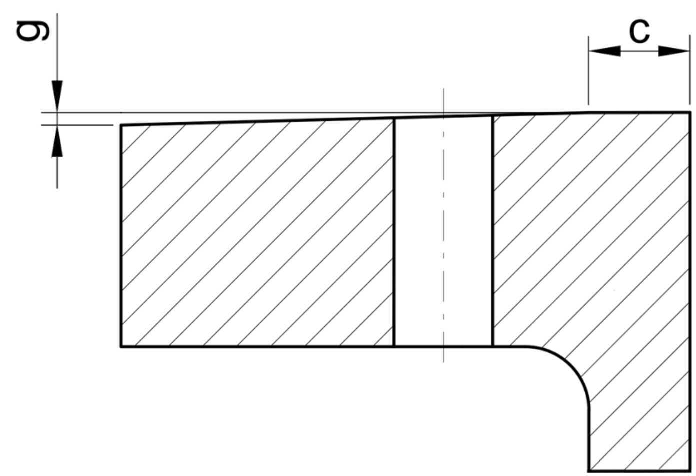
Ram ➡ Anvil ➡ Flange

30 blows/min, 3000 kJ, 200 MN impact force

<u>Driving-proof flange design</u>

Inclination towards inside

Load transfer through outer flange



Design Characteristic – Monopile Flange

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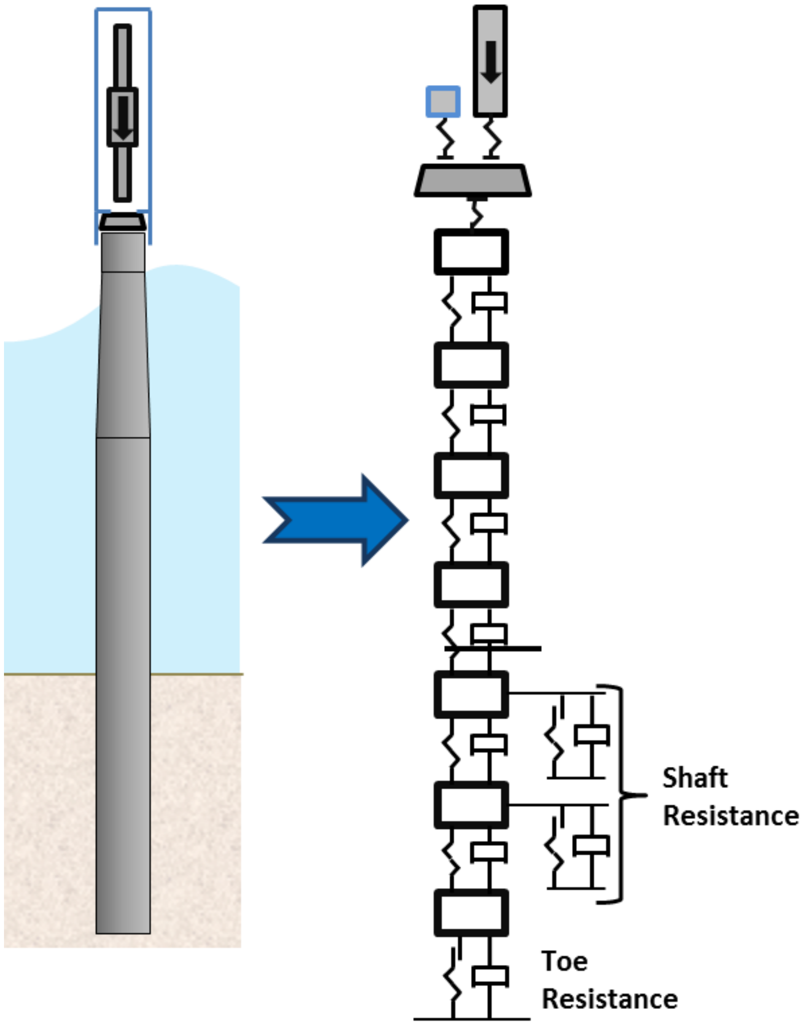
Pile-Driving Analyses – Driveability Study



Wave Equation Analysis

Stress wave propagation (1D Wave Equation)

$$\frac{\partial^2 w}{\partial t^2} = c^2 \frac{\partial^2 w}{\partial z^2} \qquad c = \sqrt{\frac{E}{\rho}} \approx 5200\,\frac{m}{s}$$

Soil resistance

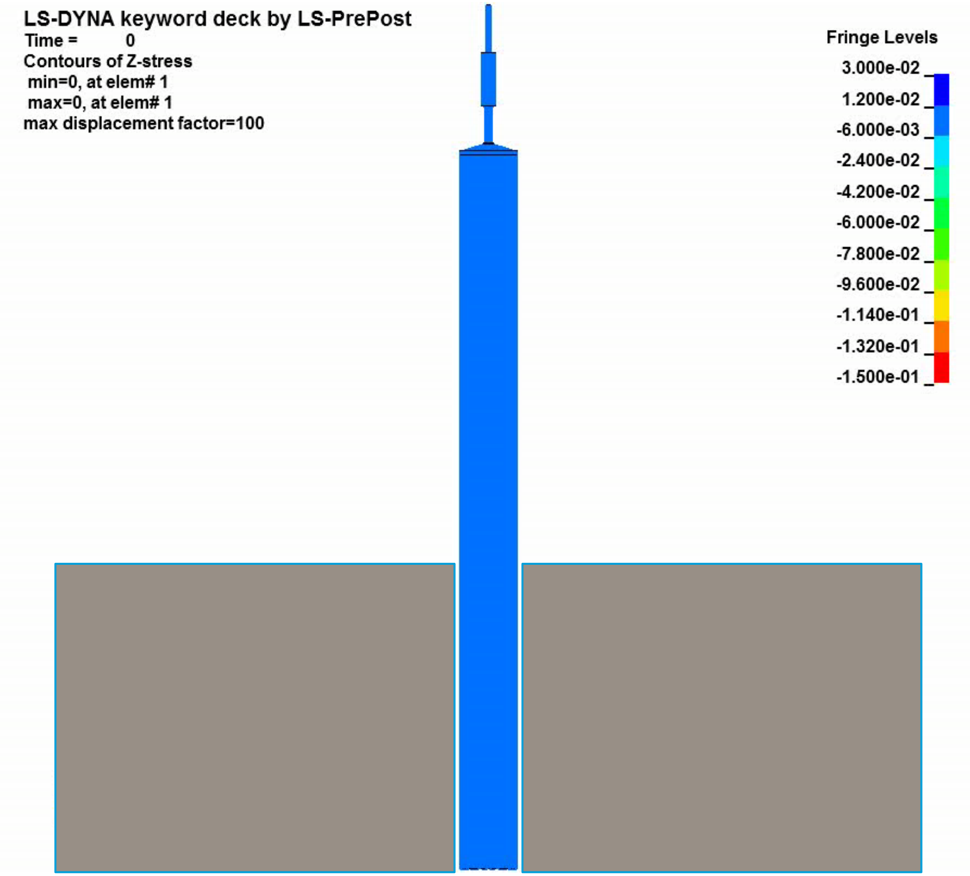
– Spring-Damper model with in-situ soil parameters (CPT)

Outcome:

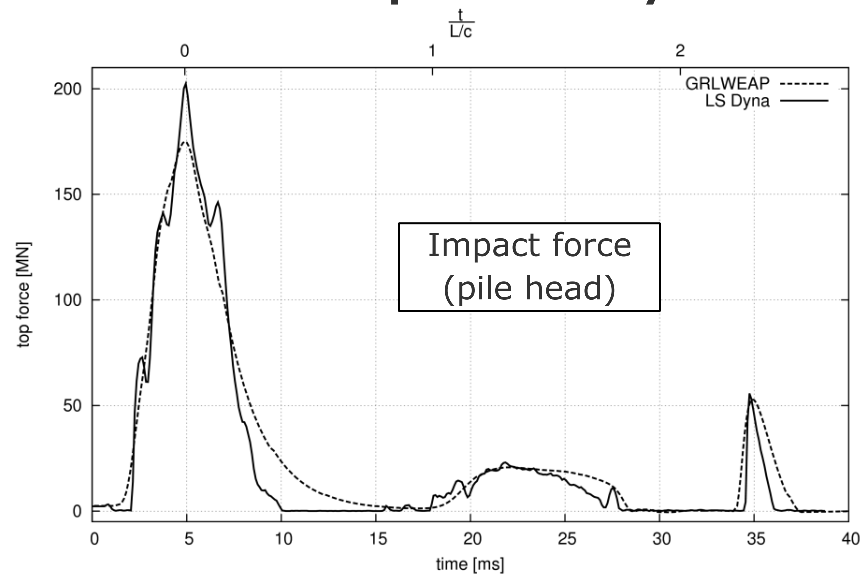
– Blow-Count (blows/penetration depth)
– Axial stresses

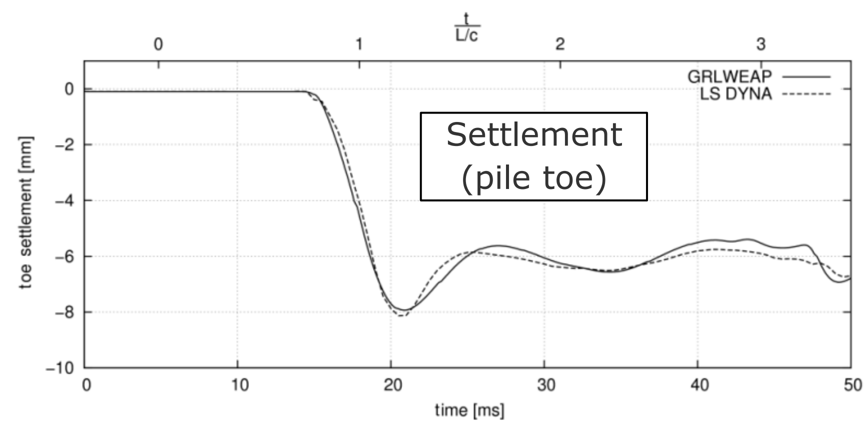
Pile-Driving Analyses – Detailed Finite Element Model

Transient dynamic FE Analysis



Validation of FE-Model against Wave Equation Analysis





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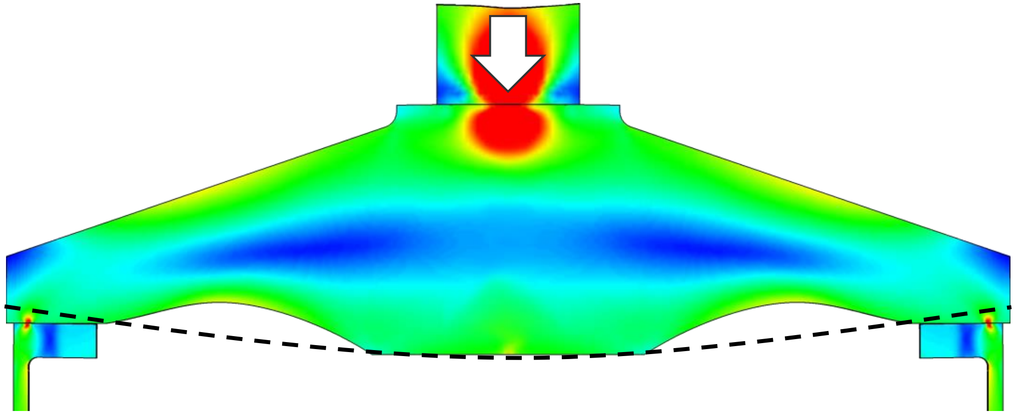
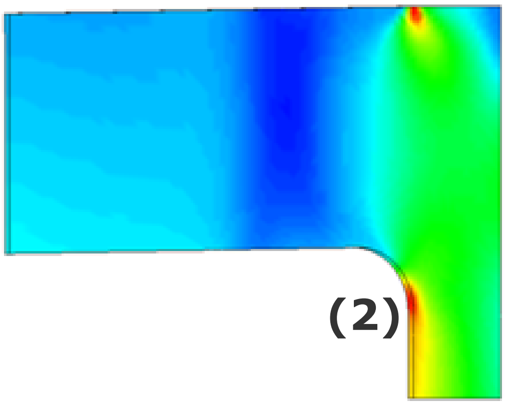
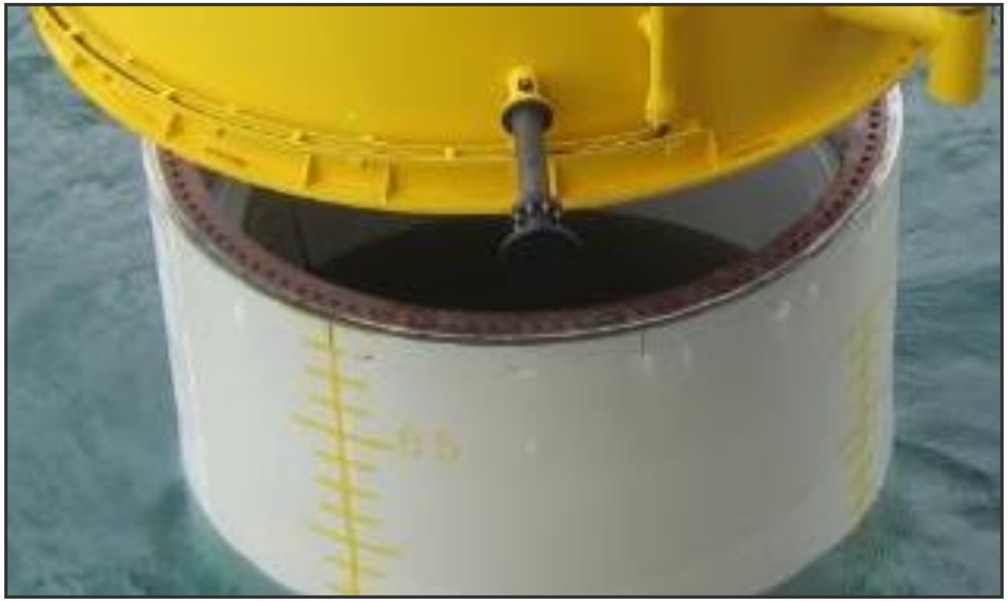
Flange Loading – Hot Spots







Flange Surface - ’Polished’ contact edge, *Sandbank, www.blog.vattenfall.de*

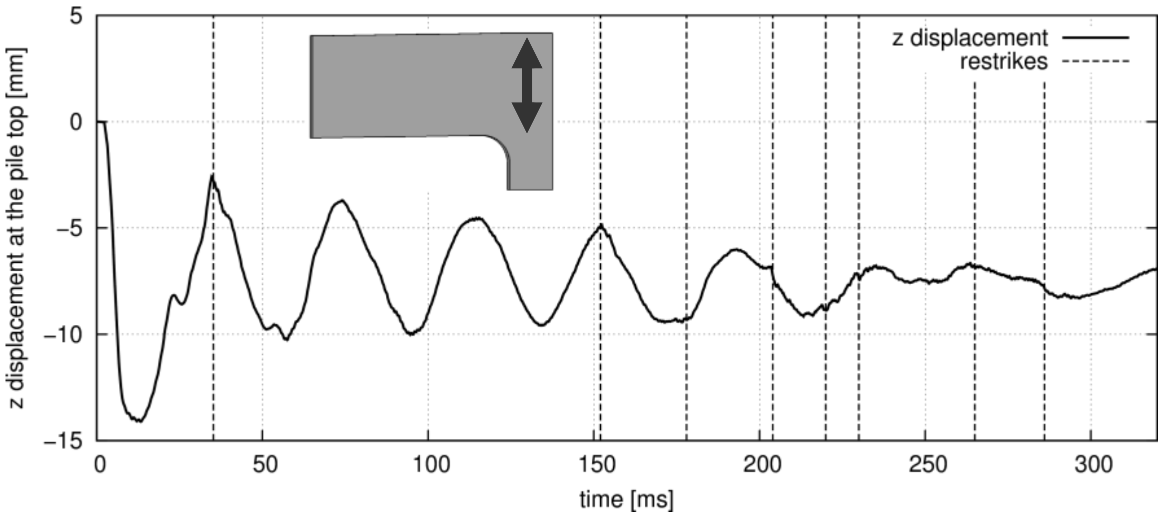
(1) Flange surface

- Local plastification at contact edge
- ‘Polished ring’ visible on-side

(2) Flange neck

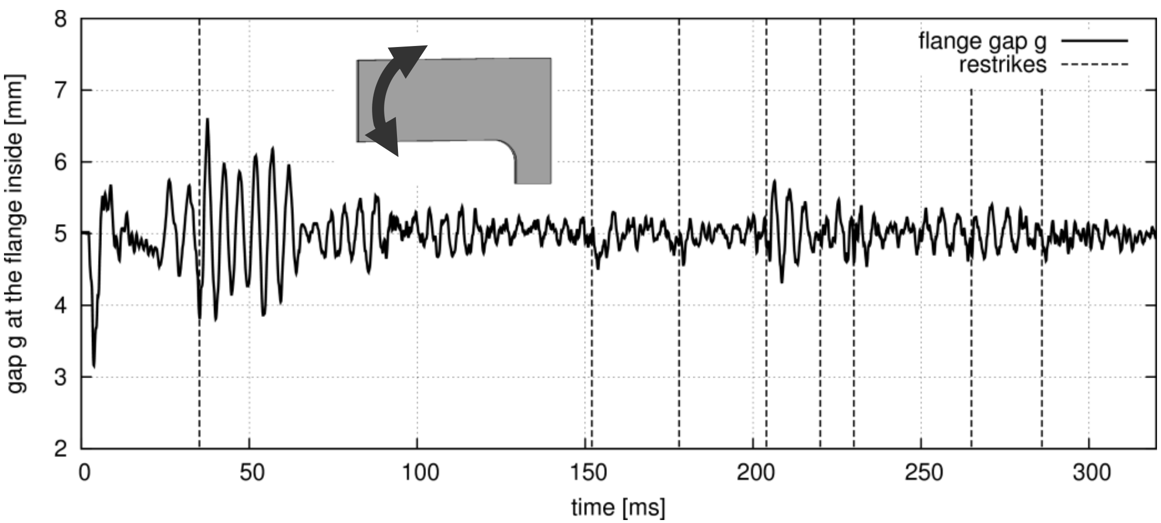
- Stress wave propagation through ‘bottleneck’
- High stress utilization

Flange Loading – Initiation of Oscillation

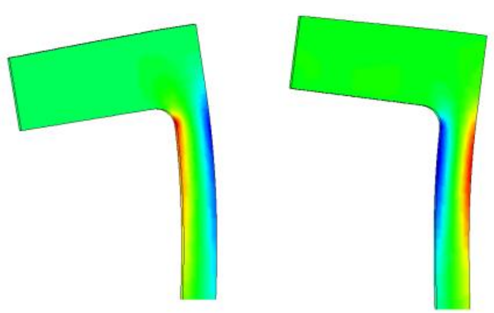


Vertical oscillation

- 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

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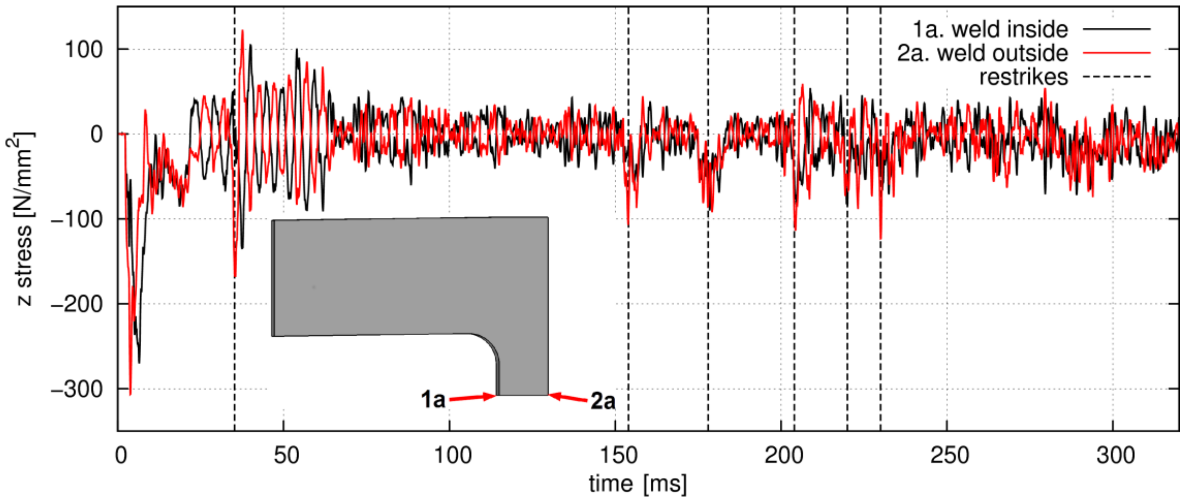
Flange Loading – Driving induced Fatigue Damage



Cyclic loading (flange weld)

- $\mathbf{n_i}$ (number of strikes)

Cumulated damage
$D = \sum D_i \cdot n_i \approx \mathbf{0.3 \ldots 0.4}$

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

- Mitigating measures
  – Increased wall thickness: Δt = 5mm ➔ -15 % operational damage
  – Reduced impact energy: $0.75 \cdot E_{Hammer}$ ➔ -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!

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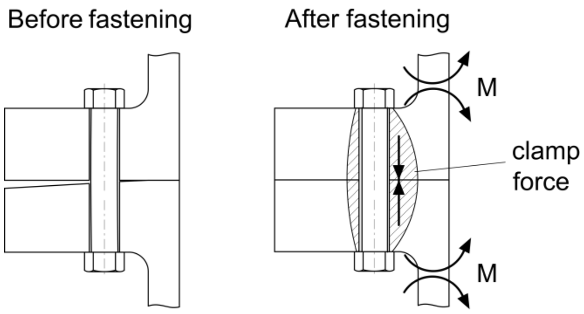
App. 01 Optimized flange geometry – Design Driver

Flange inclination (g)

Compromise

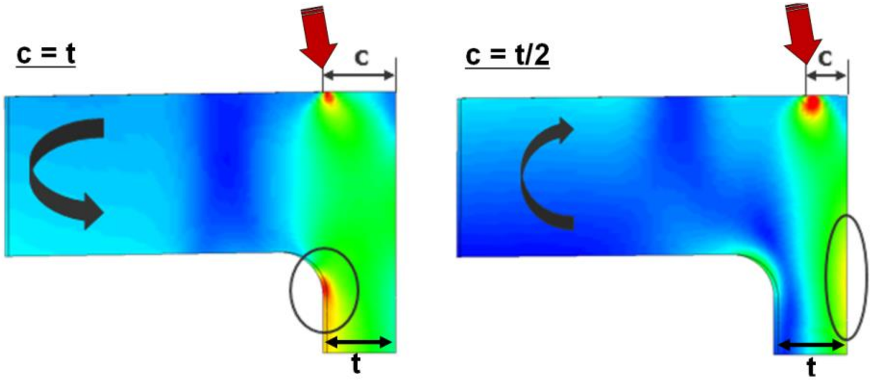
- Increase **g** to ensure that loads are only transferred through the defined contact area
- Minimize **g** to ease offshore installation (gap of MP-TP flange connection closed by tightening of bolts / shim plates)



Contact width (c)

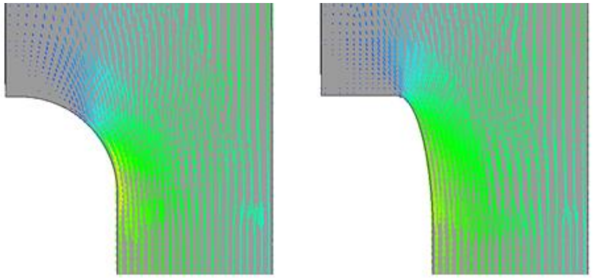
Major influence on load distribution

- 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

Gripper Arm, www.houlderltd.com

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 mm**

Considered by modelling of sinus shaped contact surface

Confirmation of anvil/flange manufacturing tolerances by measuring

Inspection of the anvil (wear effects) before each installation