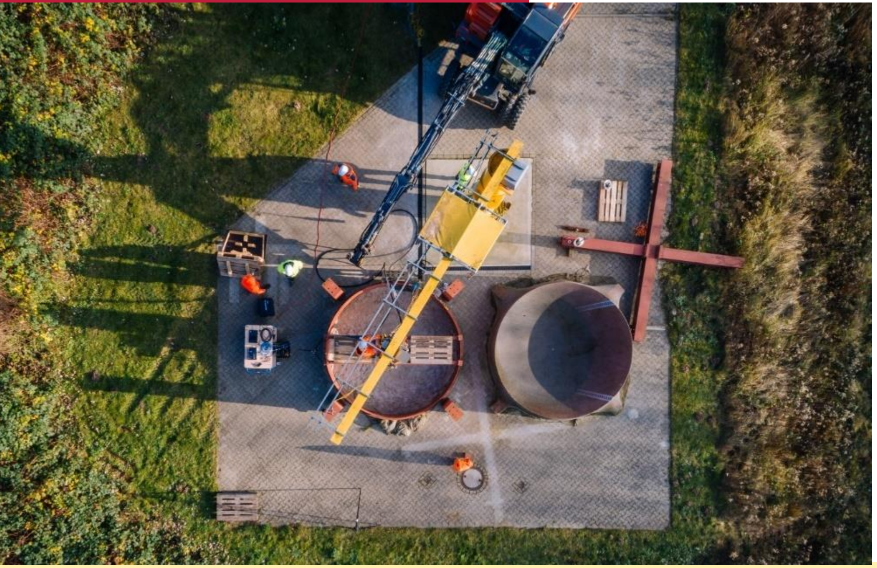
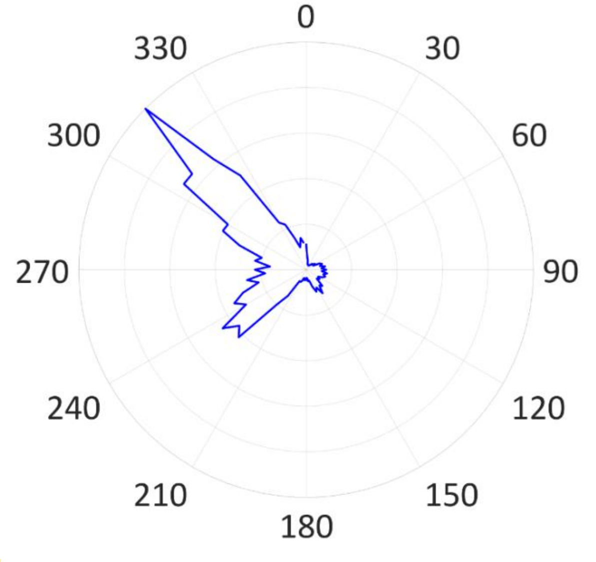
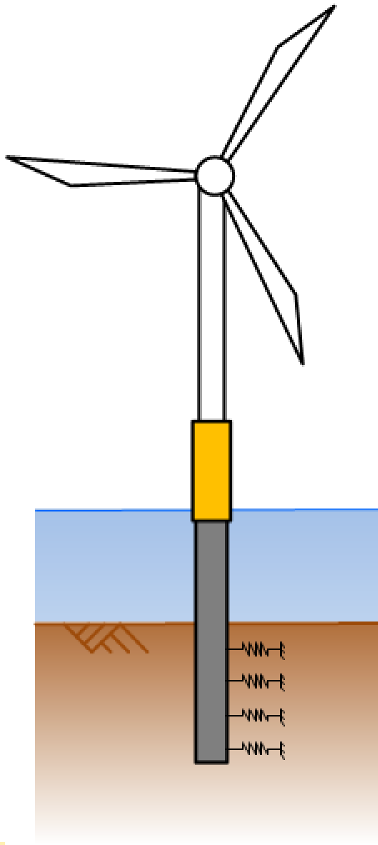
Technische Universität Braunschweig

FZK Forschungszentrum Küste







Pile head deflection of monopile foundations due to cyclic lateral loading from changing directions

Philipp Stein, Nils Hinzmann, Jörg Gattermann, Joachim Stahlmann

Institute for Foundation Engineering and Soil Mechanics
Technische Universität Braunschweig

Monopile Foundations

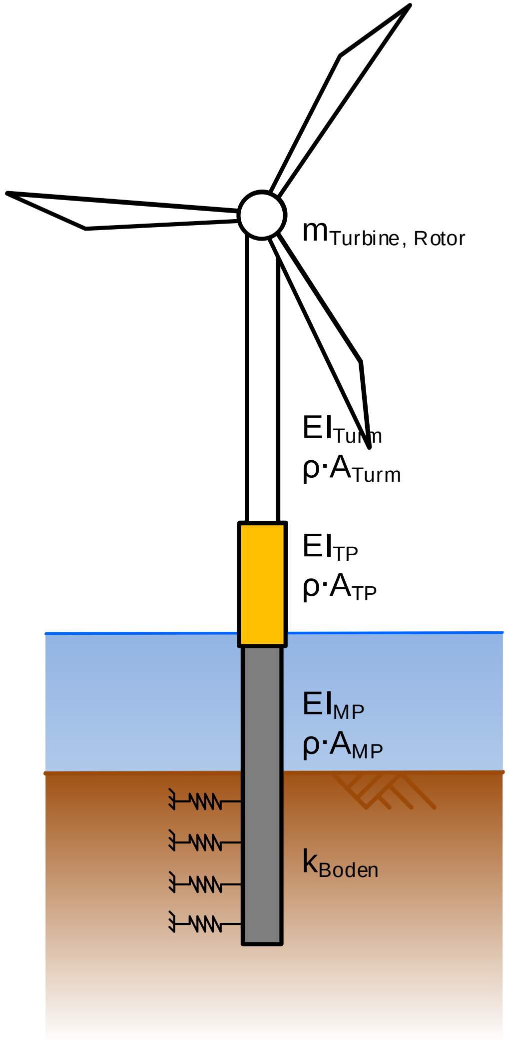
monopiles most common foundation for OWT

open questions on lateral bearing capacity

- diameter effect
- small strain stiffness
- influence of cyclic loading

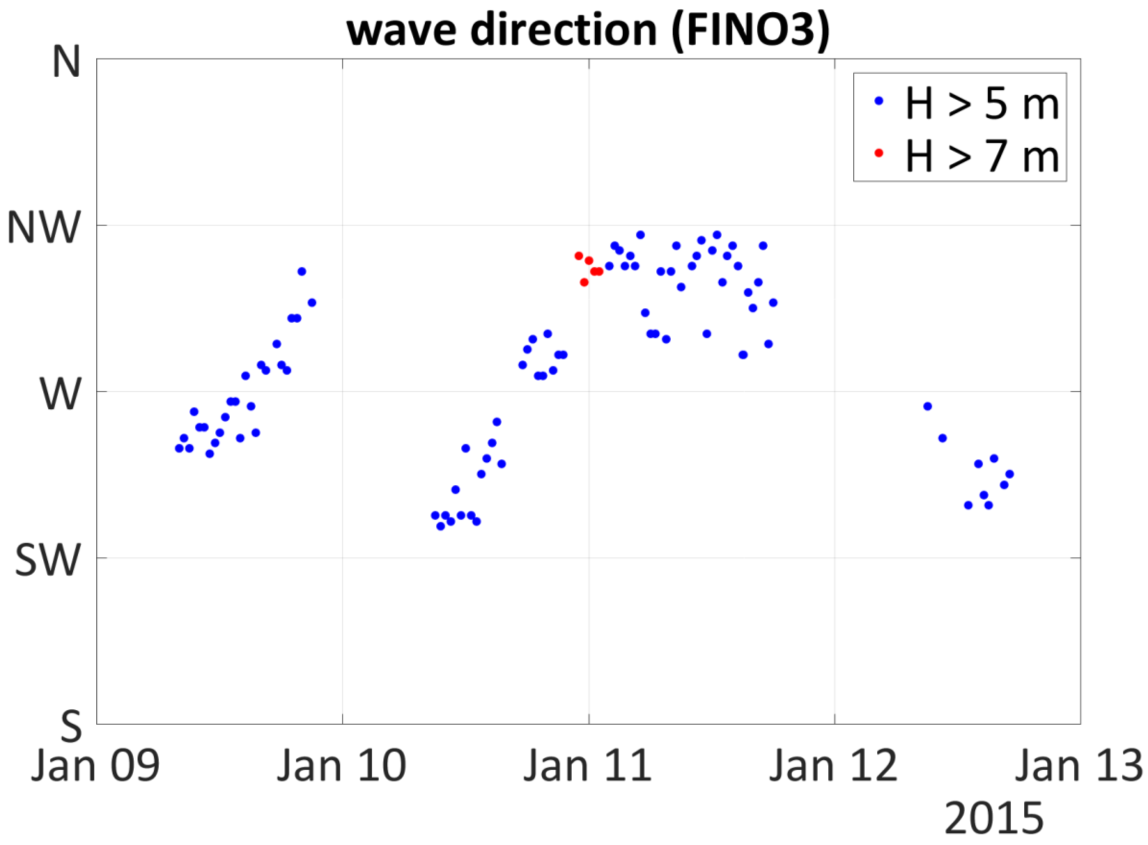
soil stiffness

- load-displacement behaviour
- structure dynamics

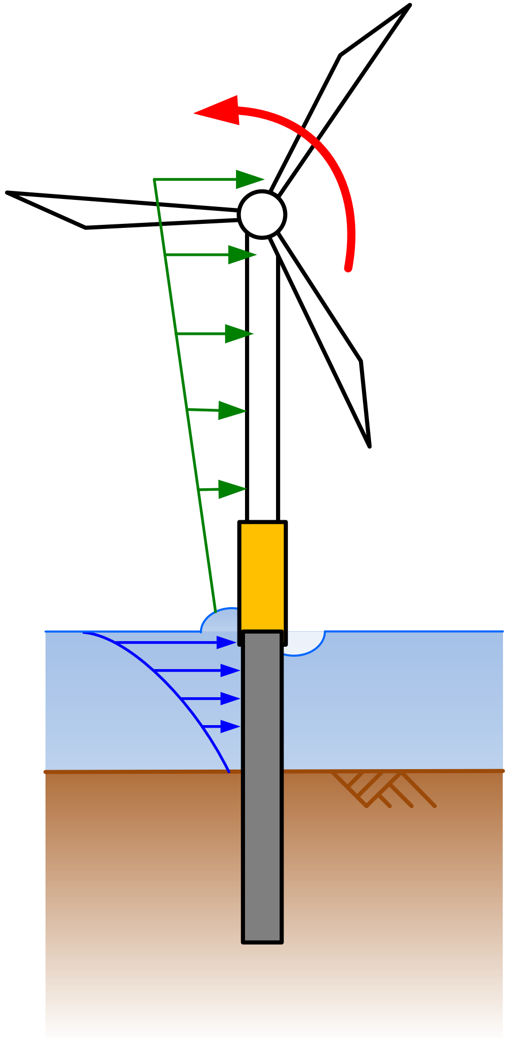


Cyclic Loading

load direction (FINO measurements)



wind
wave
turbine

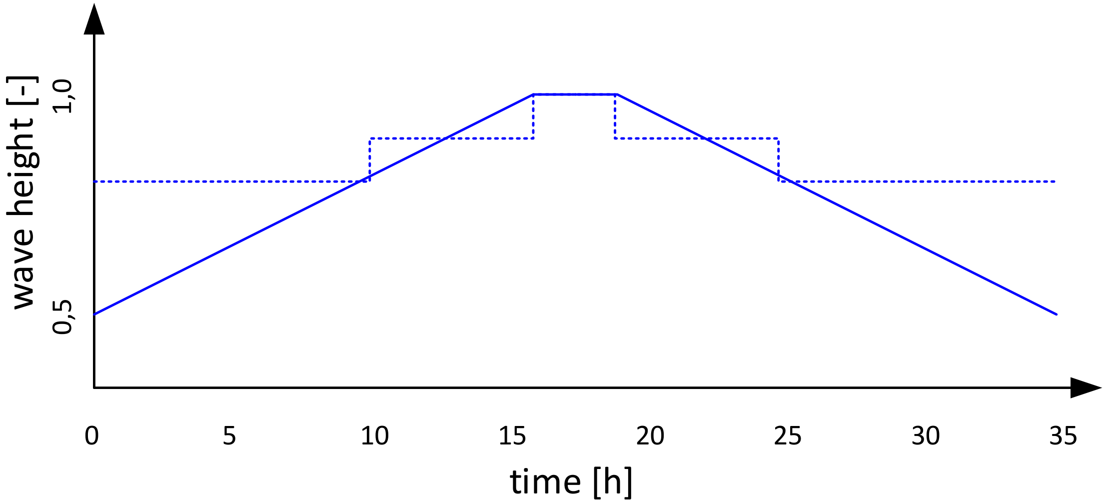


Cyclic Loading

number of load cycles (storm event accd. to BSH)

T ≈ 10,5 s/cycle (50 yr storm)

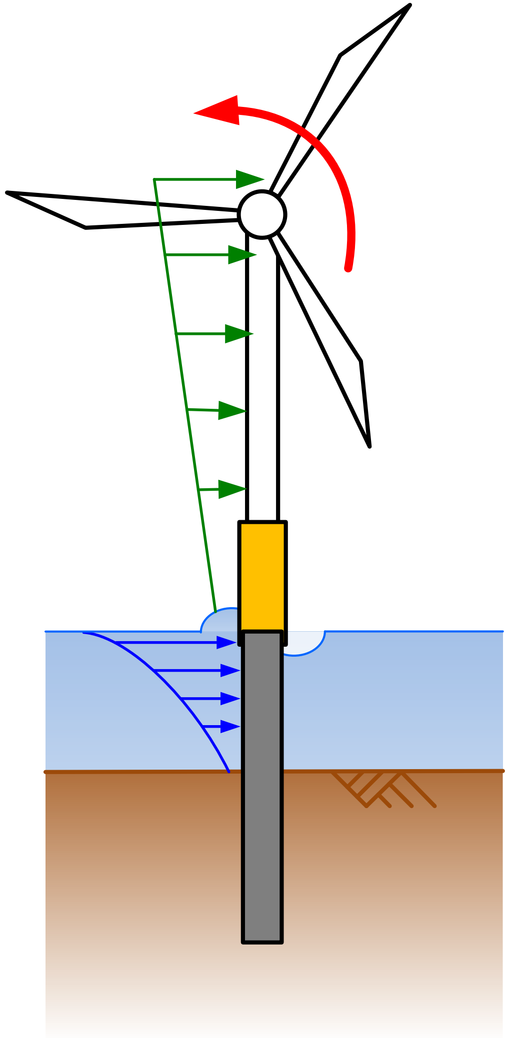
35 h / 10,5 s/cycle = 12.000 cycles



wind

wave

turbine



Cyclic Load-Displacment Behaviour

accumulation of displacements

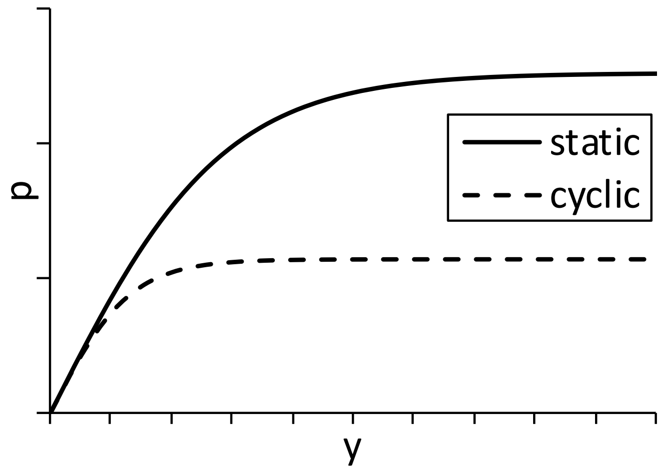
- cycle count
- loading direction

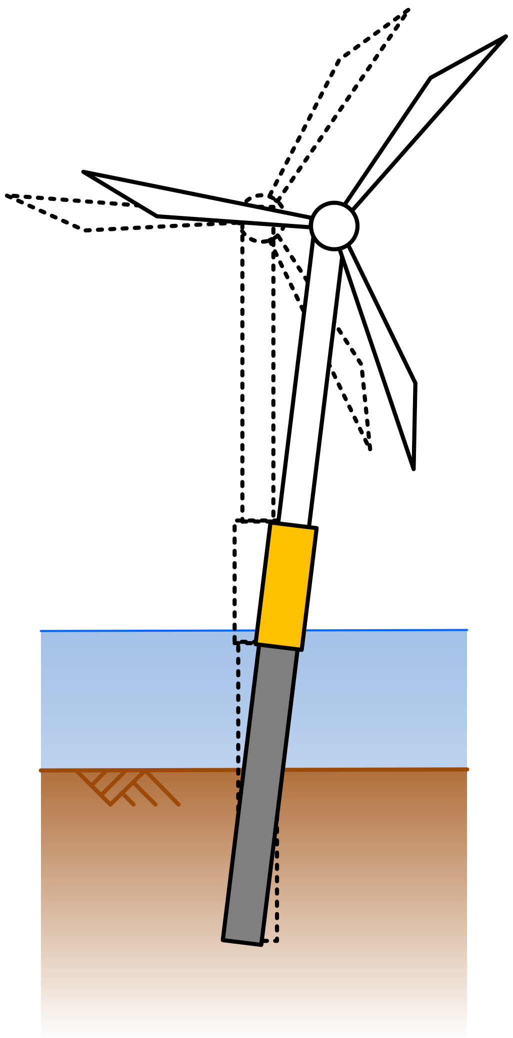
design guidelines (e.g. API, 2014)

- equivalent loads
- (cyclic) p-y curves

cyclic p-y curves

→ reduction of bearing capacity
→ no effect on initial stiffness
→ no consideration of (changing) loading direction





Scale Model Tests

scale approx. 1:13

soil

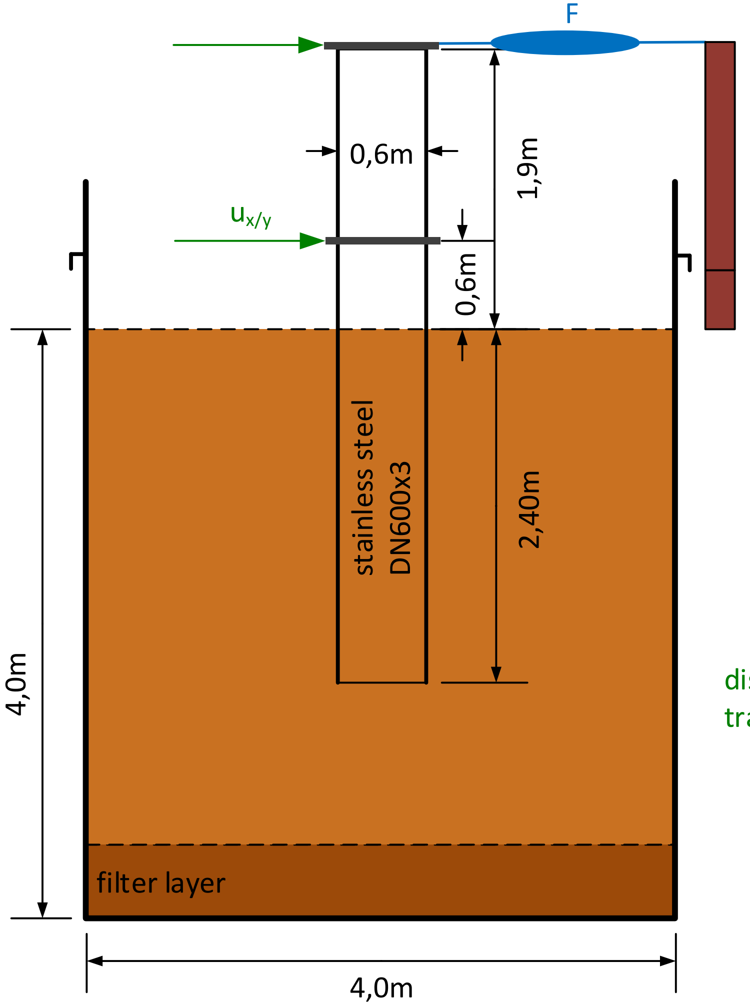
- fine sand
- dense
- saturated

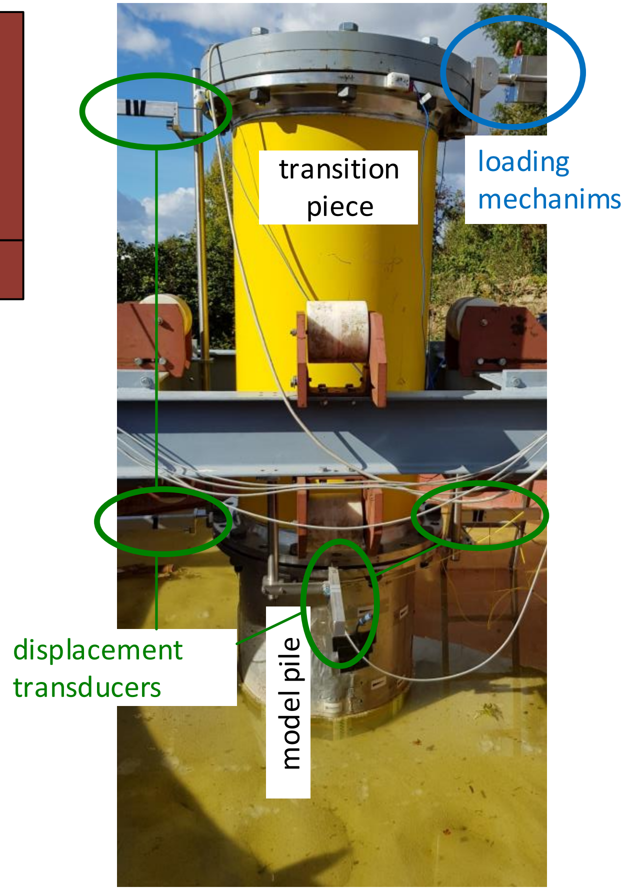
pile installation

- impact driven
- vibratory driven

loading

- cyclic (N = 12,000; each phase)
- variable loading direction (0°, 90°)





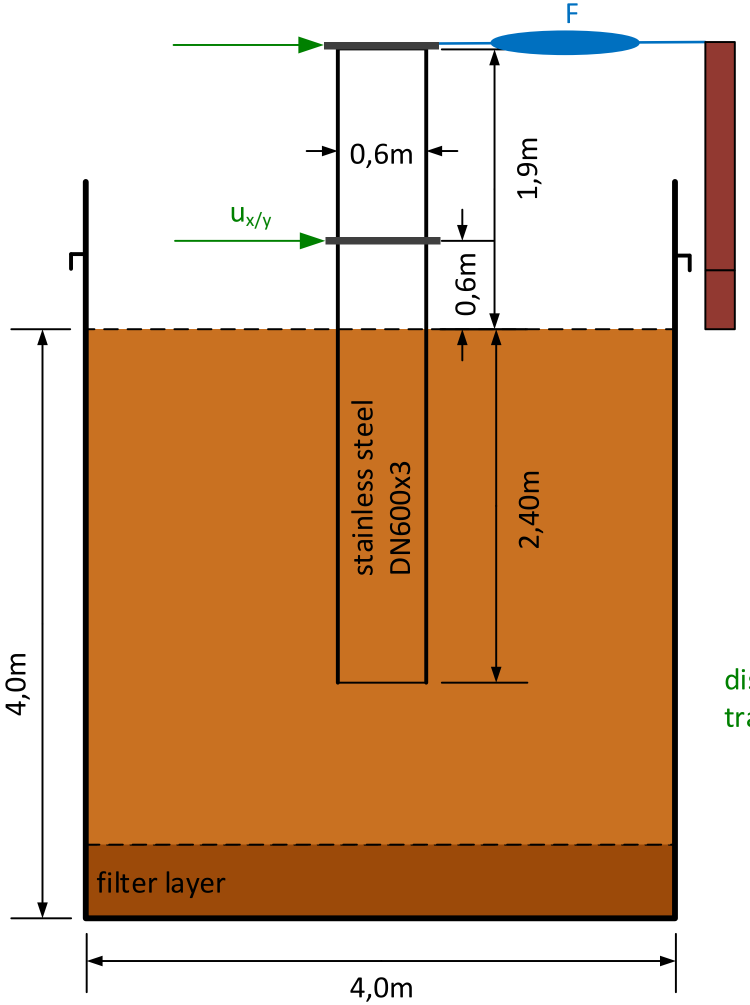
Measurement Program

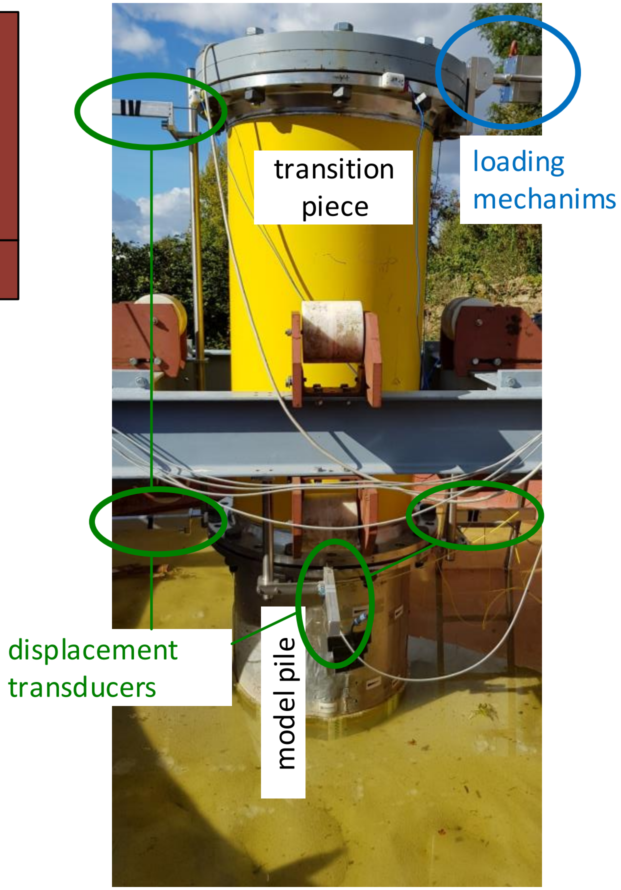
cyclic lateral loading

- applied load — F(t), N
- pile head displacement — u(t)

→ load-displacement curve — u(F)

→ displacement accumulation — u(log(N))





Cyclic Lateral Load Test

tests

- Z07
- Z05

installation method

- vibro pile driving

results

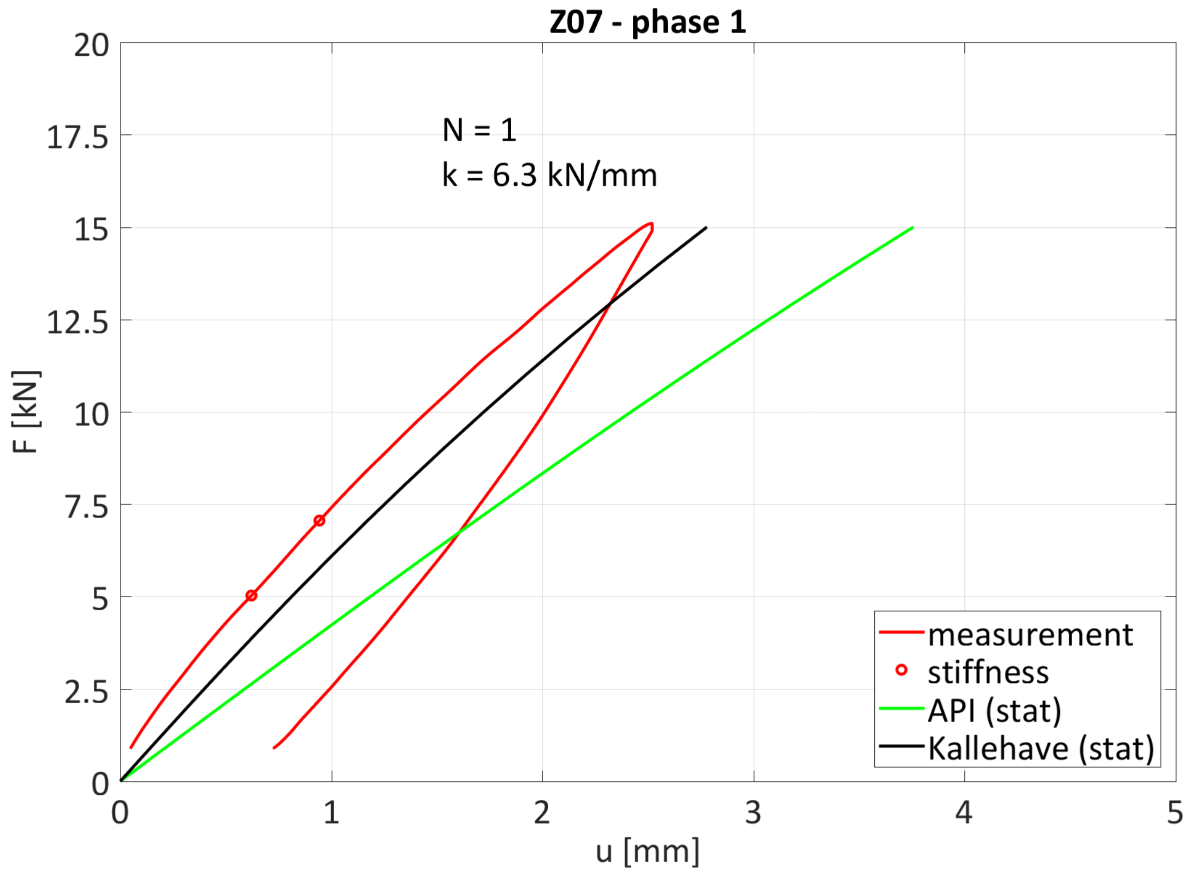
- pile head stiffness
- displacement accumulation

loading scheme

phase	load	direction	cycles
1		0°	12.000
2	1 .. 15 kN	90°	12.000
3		0°	12.000
4	5 .. 20 kN	0°	12.000
5	1 .. 15 kN	90°	12.000

Pile Head Stiffness

load displacement diagram



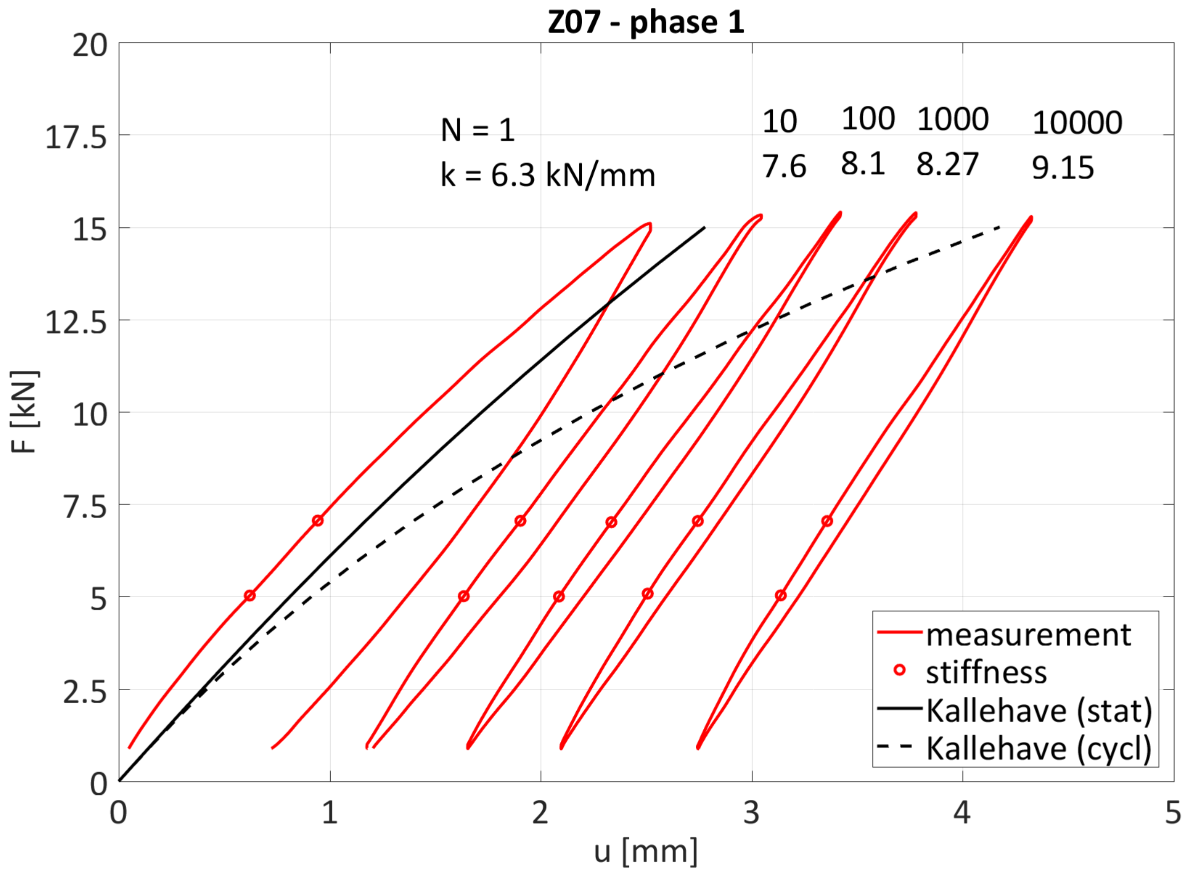
pile head stiffness (secant stiffness)

- API [2014] underestimates pile head stiffness
- Kallehave [2012] gives good estimation of pile head stiffness (for first cycle)

The calculations presented in this publication were performed with the IGtHPile software developed by the Institute of Geotechnical Engineering (IGtH), Leibniz Universität Hannover, Germany.

Pile Head Stiffness

load displacement diagram



pile head stiffness (secant stiffness)

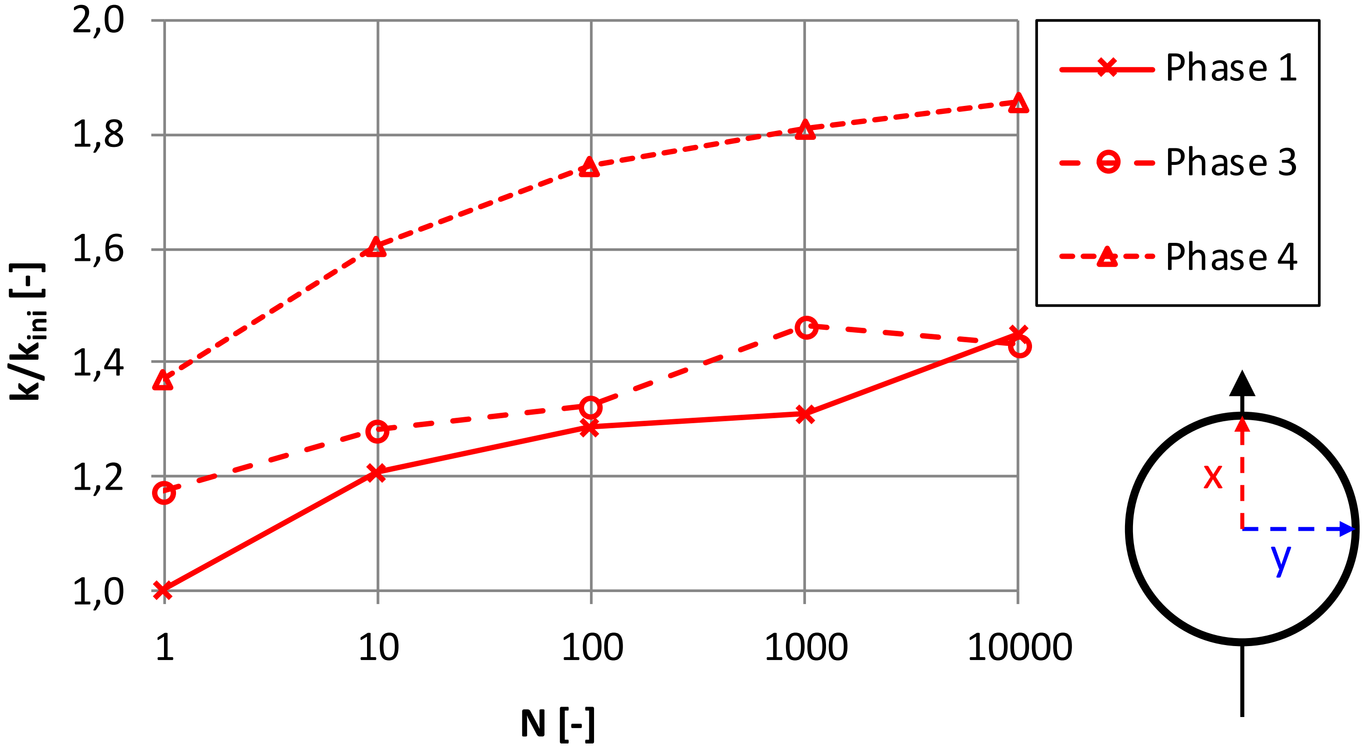
- API [2014] underestimates pile head stiffness
- Kallehave [2012] gives good estimation of pile head stiffness (for first cycle)
- pile head stiffnes increases with number of loads
- cyclic p-y curves do not give stiffness of Nth cycle

The calculations presented in this publication were performed with the IGtHPile software developed by the Institute of Geotechnical Engineering (IGtH), Leibniz Universität Hannover, Germany.

Pile Head Stiffness

development over number of cycles

(pile head stiffness related to first cycle)



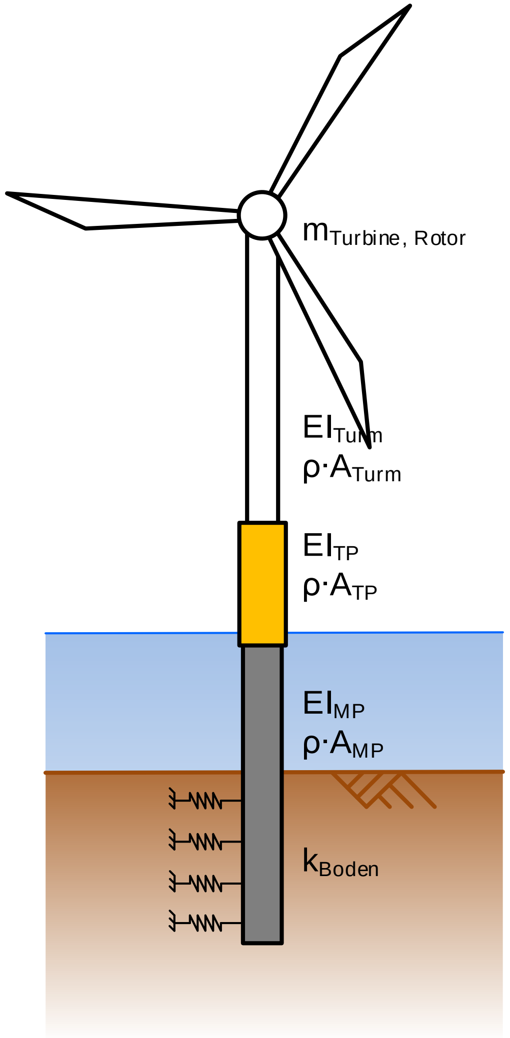
pile head stiffness (secant stiffness)

- pile head stiffness increases with number of loads
- pile head stiffness decreases due to transverse loading

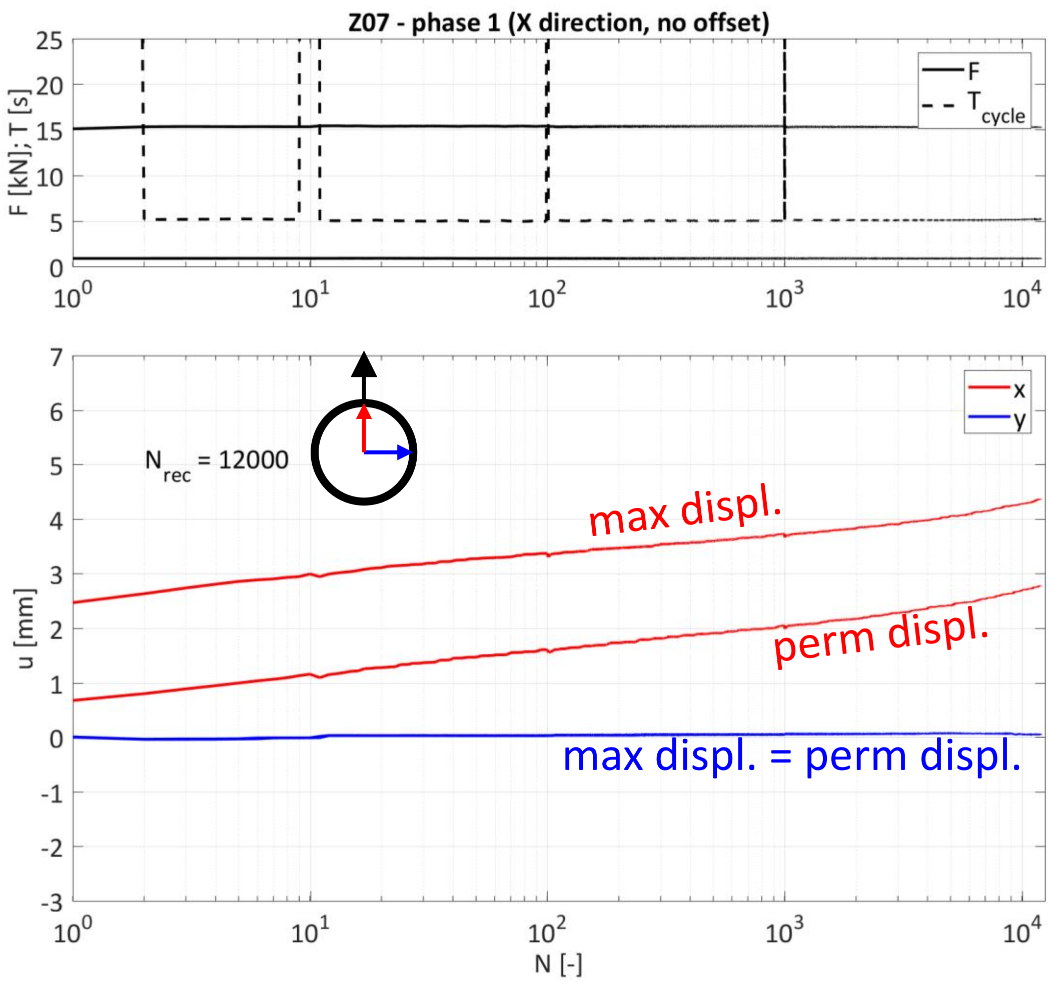
Lateral Stiffness of Monopile Foundations

soil stiffness

- crucial for eigenfrequency of OWT
- increases due to cyclic loading
- decreases due to subsequent perpendicular loading
- not predicted by (cyclic) p-y curves



Displacement Accumulation

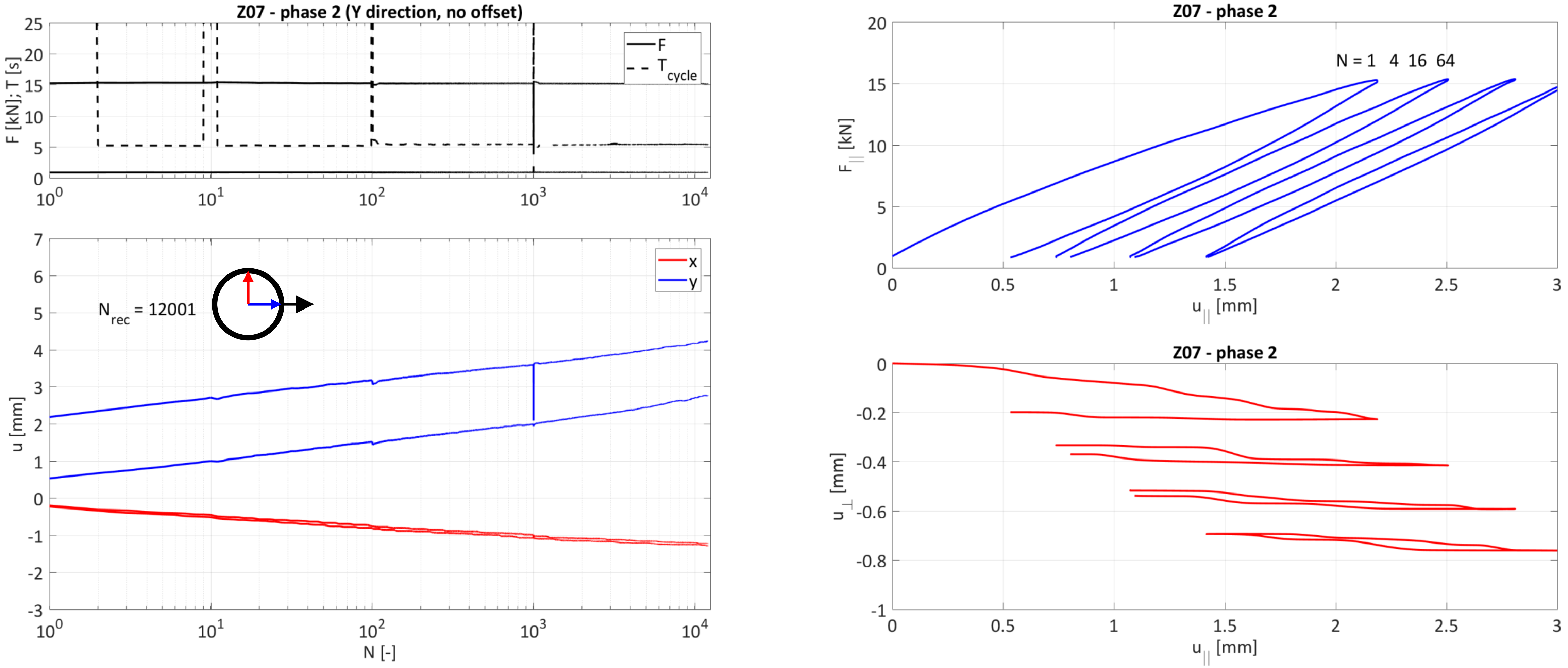


$u_N \approx u_1 + b \cdot \log(N)$

$b_x \approx 0.2$

- logarithmic accumulation of displacements

Displacement Accumulation



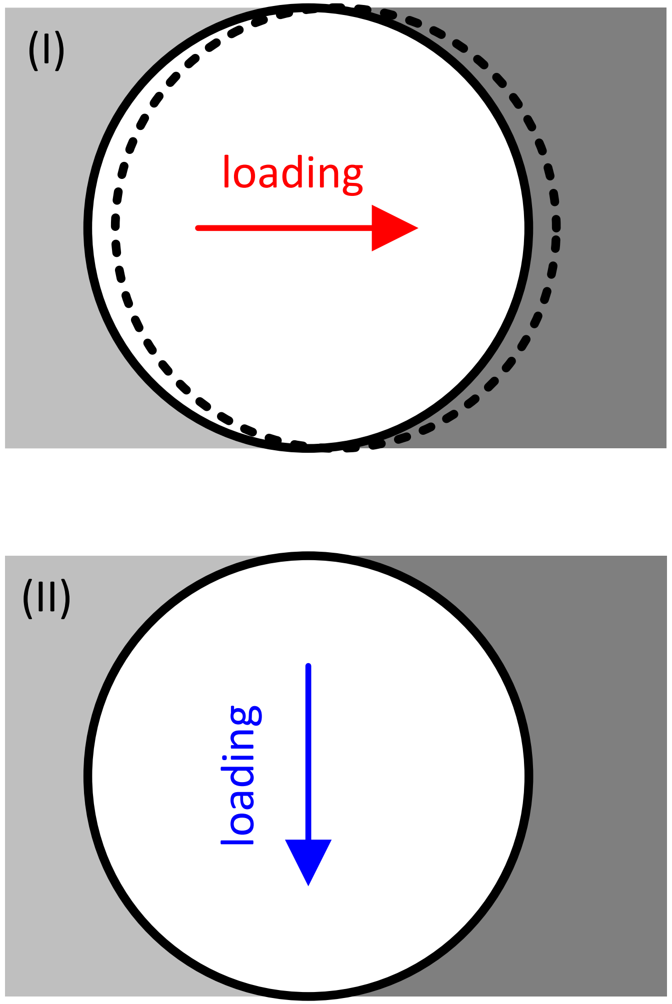
Soil Behaviour

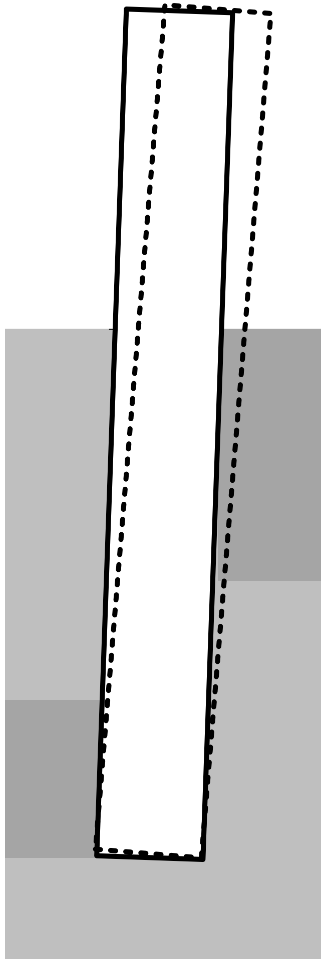
permanent displacements

- accumulation over number of cycles
- recovery due to transverse loading

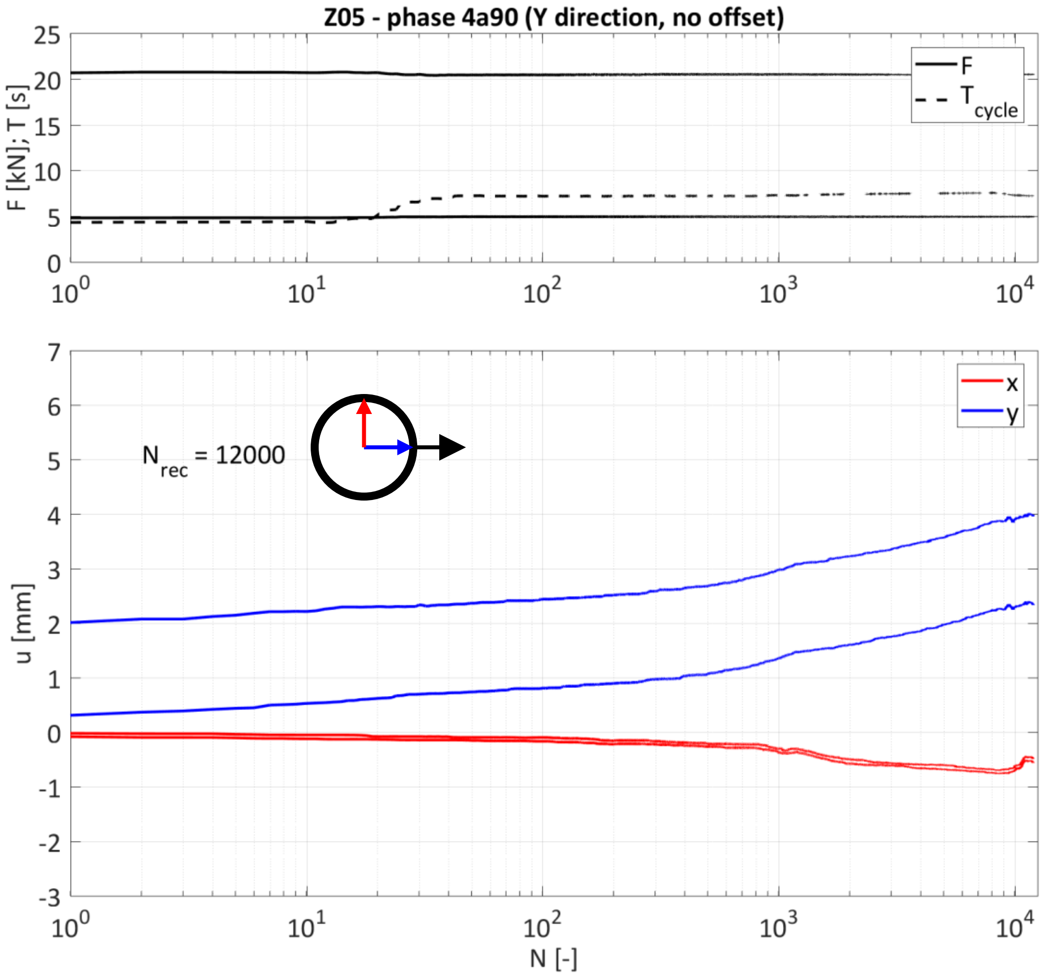
(I) compression of soil
in direction of loading
→ densification ("downwind")

(II) shear stress
due to transverse loading
→ dilatancy, loosening





Displacement Accumulation



influence of load amplitude on recovery?

phase	load	direction	cycles
4a90	5 .. 20 kN	90°	12.000
5F5	1 .. 5 kN	0°	12.000
5F10	1 .. 10 kN	0°	12.000
5F15	1 .. 15 kN	0°	12.000

Displacement Accumulation

IGB-TUBS

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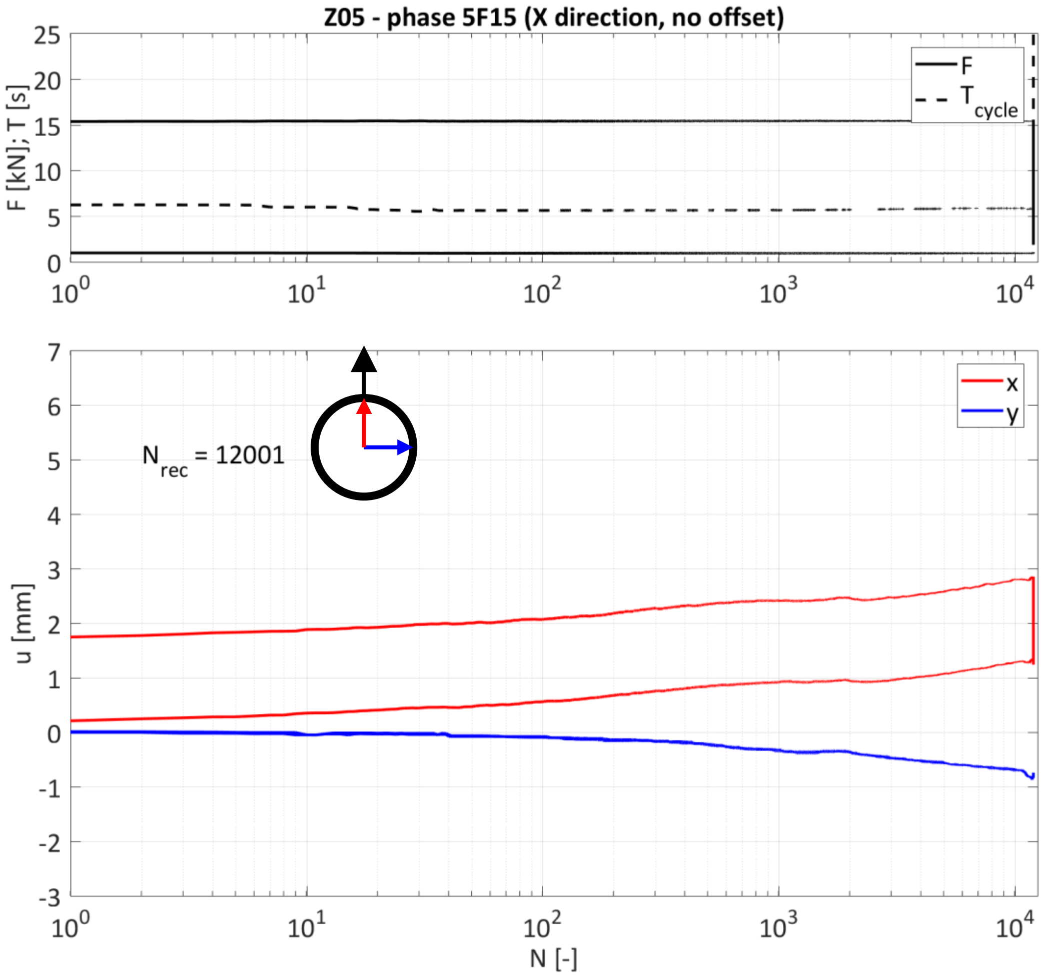

influence of load amplitude on recovery?

- Phase 4: Y direction (5..20 kN)
- Phase 5: X direction

  (1..5 kN)

  (1..10 kN)

  (1..15 kN)

→ small loads/deflections cause tranverse recovery

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Summary and Outlook

model tests

- ✓ cyclic lateral load on monopile
- ✓ changing loading direction

pile head stiffness

- increase with number of cycles
- decrease due to transverse loading

pile head displacements

- accumulation with number of cycles (log)
- recovery with transverse loading

- ○ comparison of vibrated and impact driven piles

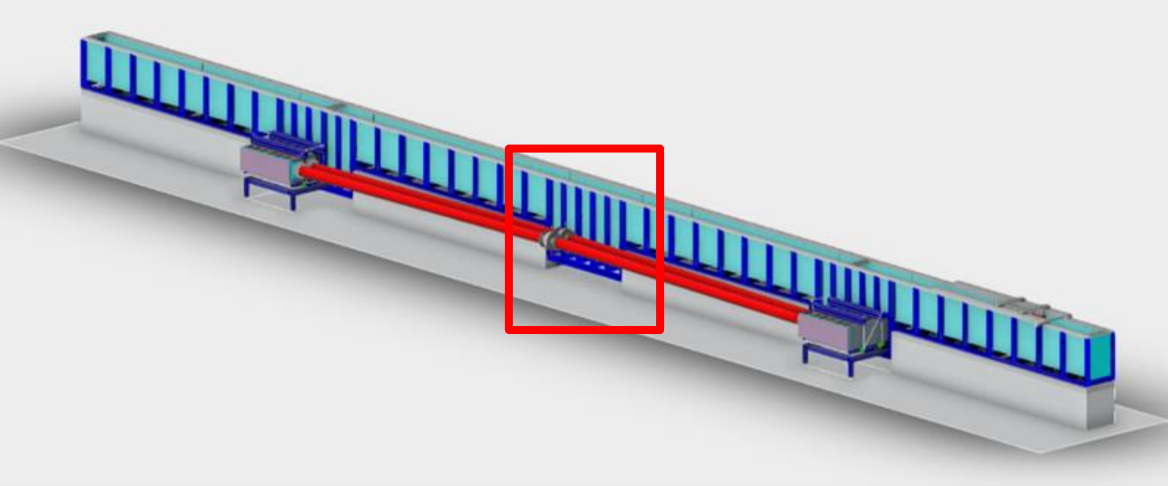
- ○ more detailed analysis
  - ○ pile bending curve
    - ➢ p-y curves (different depths)
    - ➢ soil stiffness (different depths)
  - ○ earth pressure measurements
    - ➢ stress (re)distribution

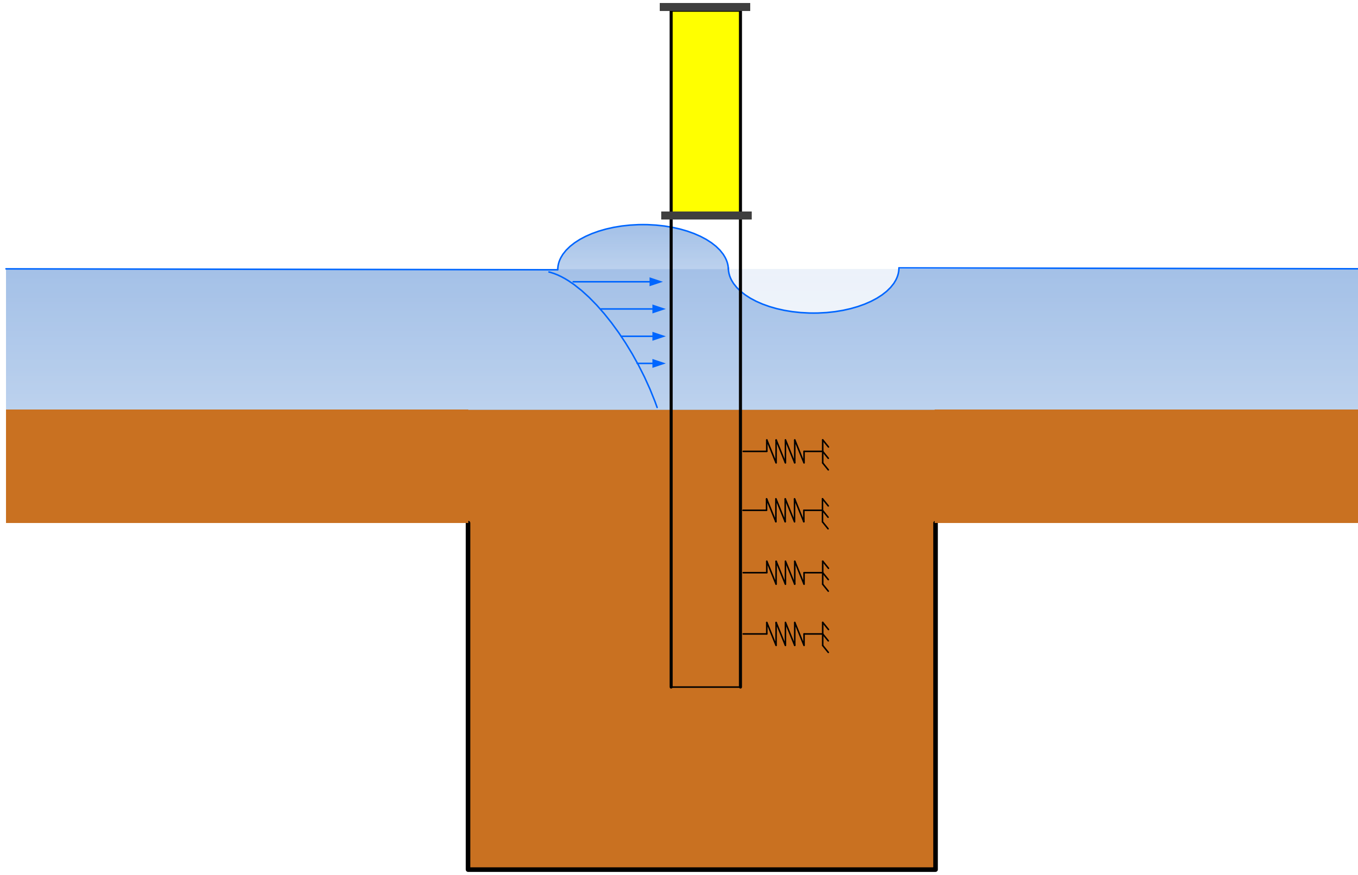
Summary and Outlook

… but still …

no fluid-structure interaction ☹

project marTech → GWKplus ☺





Research Poject CycLaMP (ZykLaMP)

scale model investigations on the load-bearing behaviour
of **cyc**lic **la**teral loaded **m**ono**p**iles
with regard to the installation method

'large-scale model investigations on the lateral bearing capacity
of impact driven and vibratory driven open ended steel pipe piles under cyclic loading'

funding code 0324133

funding agency: Projektträger Jülich
partner: Bundesanstalt für Wasserbau

Supported by:
Federal Ministry for Economic Affairs and Energy
on the basis of a decision by the German Bundestag

Questions?

Discussion!

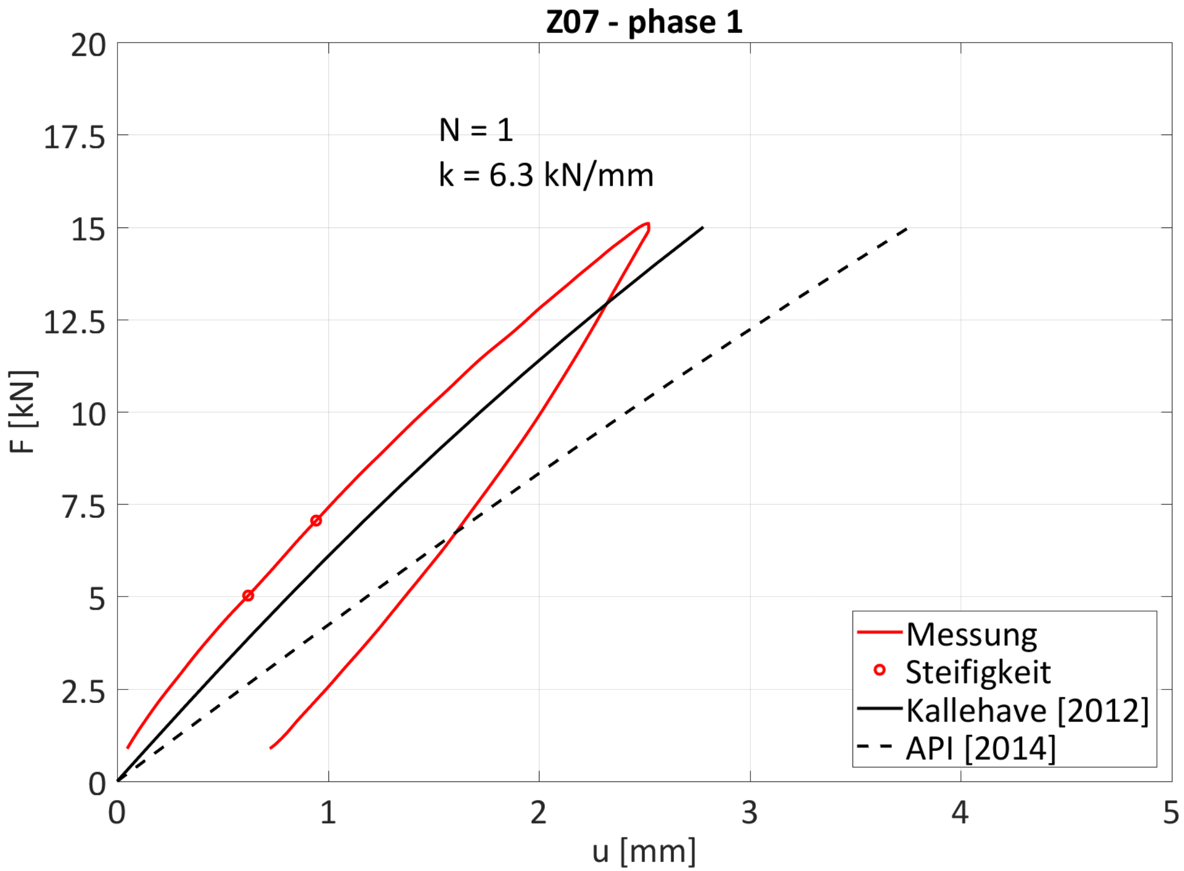
Literature

American Petroleum Institute (API): Geotechnical and Foundation Design Considerations. *ANSI/API Recommended Practice 2GEO, 1st Edition, April 2011, Addendum 1, October 2014*

Kallehave, D., LeBlanc Thilsted, C., Liingaard, M.A.: Modification of the API p-y formulation of initial stiffness of sand. *Offshore site investigation and geotechnics: integrated technologies – present and future, September 12-14 2012, London, S. 465-472*

Modifikation nach Kallehave et al. [2012]

Last-Verschiebungsdiagramm



p-y-Kruven [API, 2014] aus [O'Neill & Murchison, 1983]

$$p = A \cdot p_u \cdot \tanh\left(\frac{k \cdot z}{A \cdot p_u}\right)$$

Modifikation [Kallehave et al., 2012]

$$(k \cdot z)_{\text{Kallehave}} = k_{\text{API}} \cdot z_0 \cdot \left(\frac{z}{z_0}\right)^{0,6} \cdot \left(\frac{D}{D_0}\right)^{0,5}$$

Modellversuche

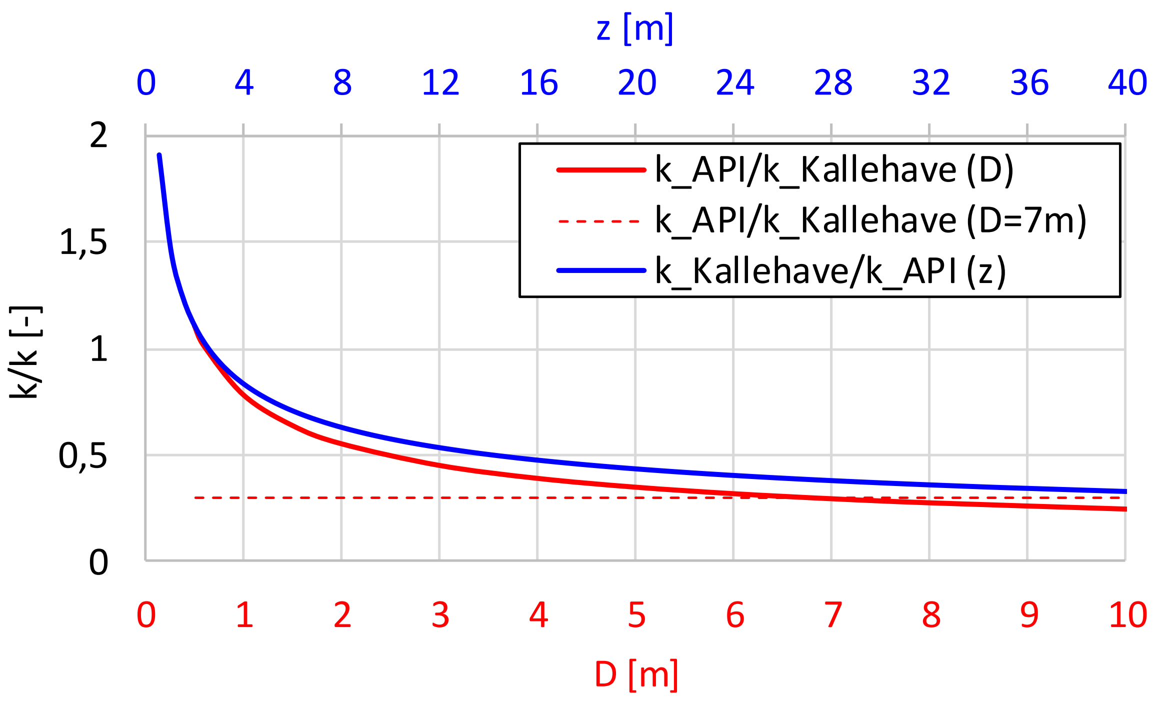
$D = D_0$

$z < z_0$

Diese Berechnungen wurden mit der Software IGtHPile durchgeführt, entwickelt vom Institut für Geotechnik (IGtH) der Leibniz Universität Hannover.

Modifikation nach Kallehave et al. [2012]

Einflussfaktoren D, z



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Modellversuche

$D = D_0$

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