PREDICTION OF LONG-TERM DEFORMATIONS OF OFFSHORE WIND TURBINE FOUNDATIONS WITH A HIGH-CYCLE ACCUMULATION MODEL

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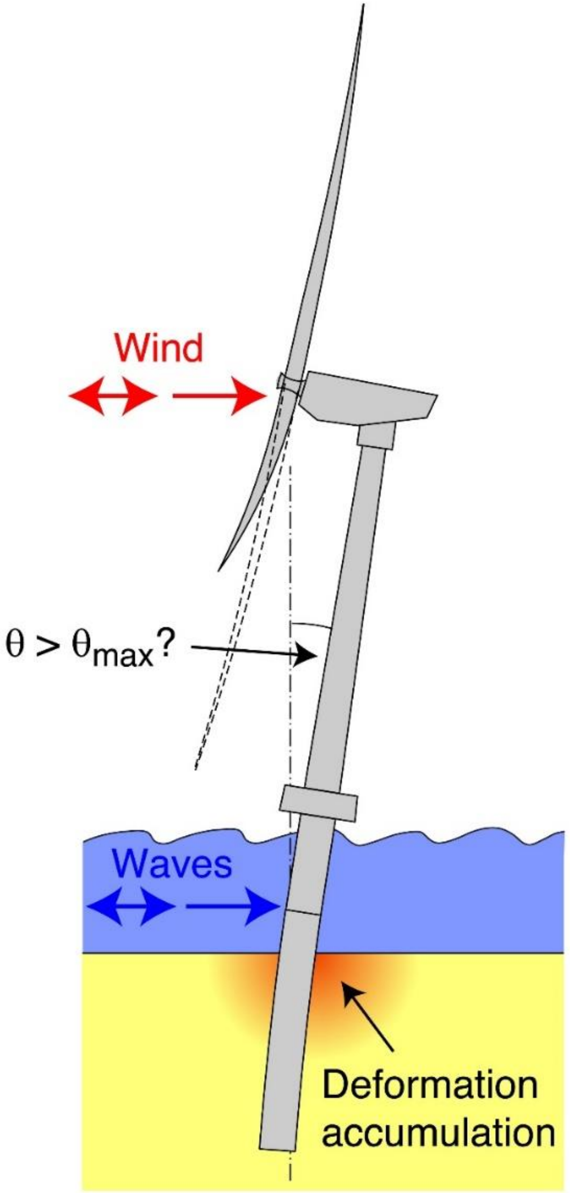
Motivation

High-cyclic
- Large number of cycles ($N > 10^4$)
- Small amplitudes ($\varepsilon^{ampl} \leq 10^{-3}$)



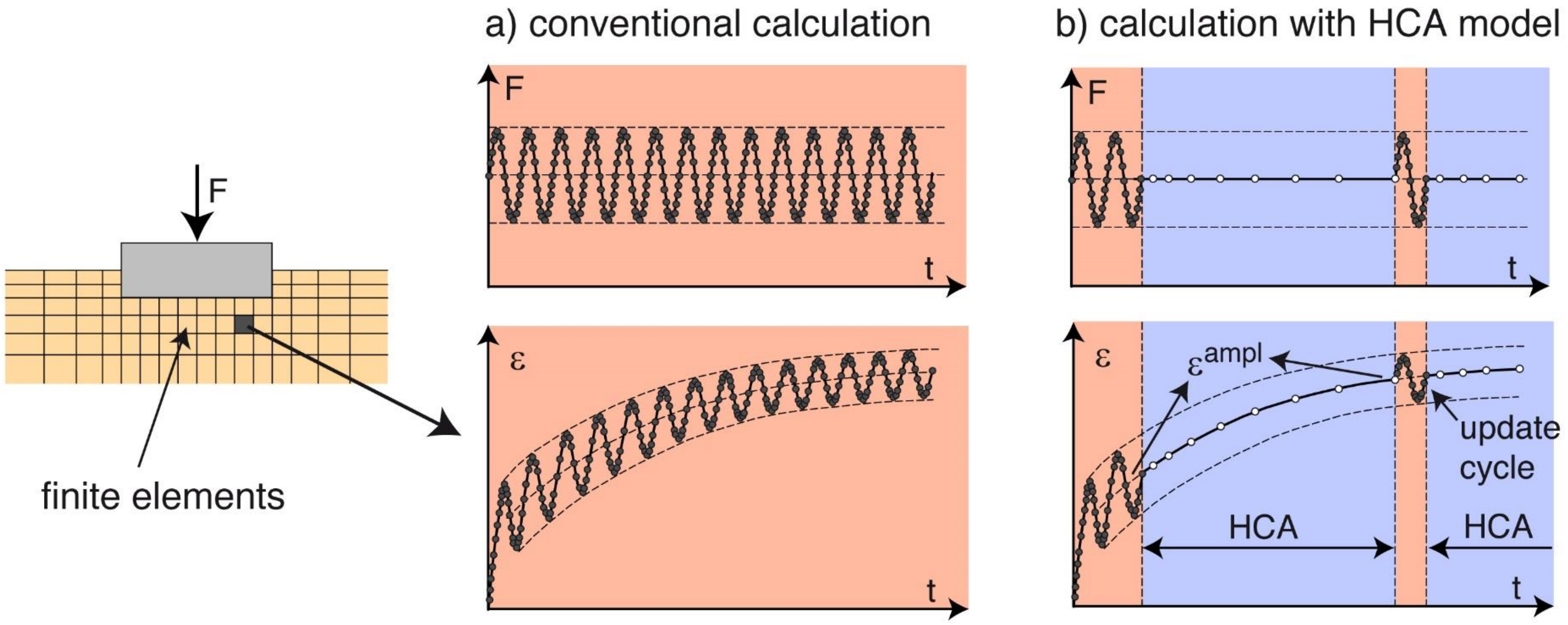
- High-cyclic loading of OWT foundations caused by wind and waves
- Accumulation of deformations in the soil (compaction / dilatancy)
- Tilting of offshore wind turbine → possible loss of serviceability
- Accurate prediction of long-term deformations necessary for whole lifetime
- Application of high-cycle accumulation (HCA) models for that purpose

Content

1. High-cycle accumulation (HCA) model
    - Calculation strategy
    - Equations
    - Calibration based on laboratory tests
    - Simplified calibration procedure
2. Validation of HCA model
3. Application of HCA model to OWT monopile foundations
    - Influence of soil state and loading
    - Installation effects
    - Influence of constitutive model used in combination with HCA model
    - Influence of calibration method
4. Summary

1. High-cycle accumulation model

Calculation strategy



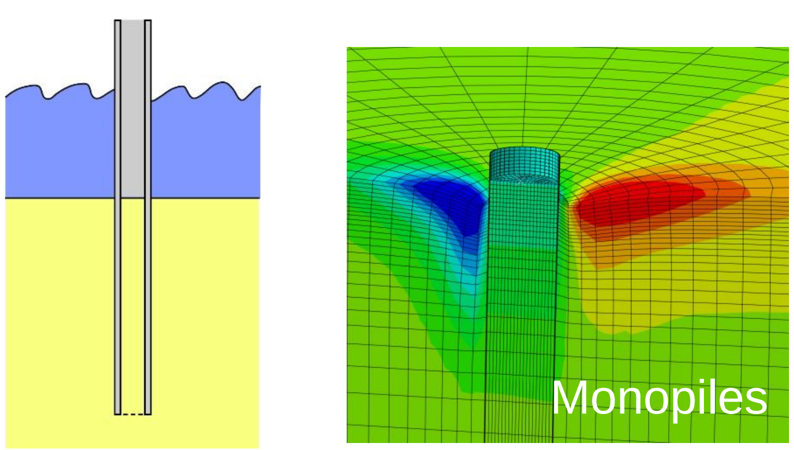
Characteristics of HCA models:

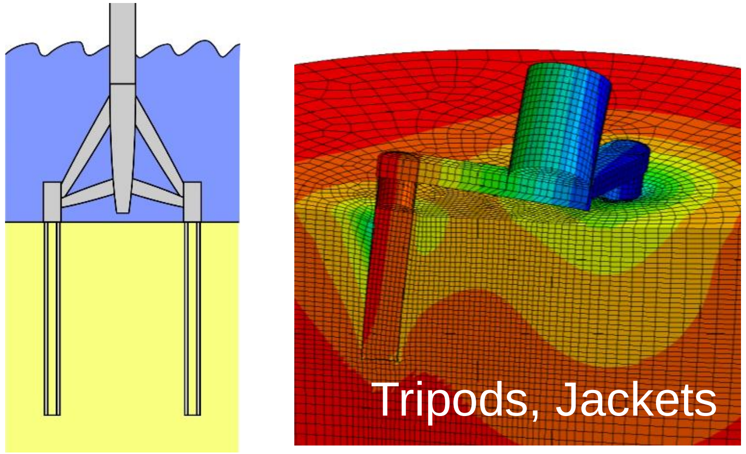
- Dependence of strain accumulation rates on various parameters can be described easier
- Less numerical error, less numerical effort
- No restrictions regarding the maximum number of cycles
- Input of the accumulation model: Strain amplitude ε^{ampl} (determined from the cycles calculated conventionally), void ratio, average stress, …

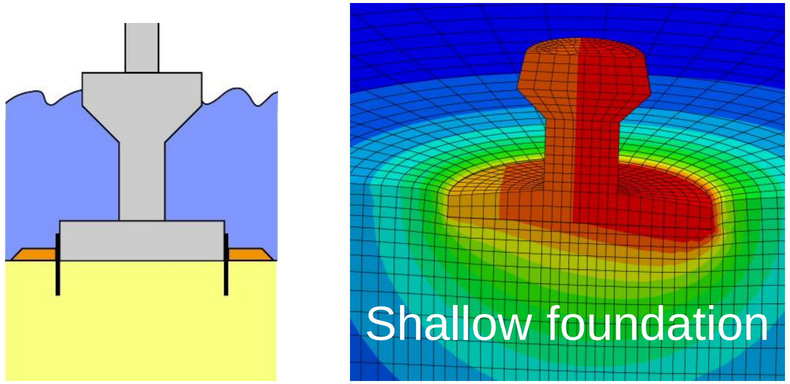
1. High-cycle accumulation model

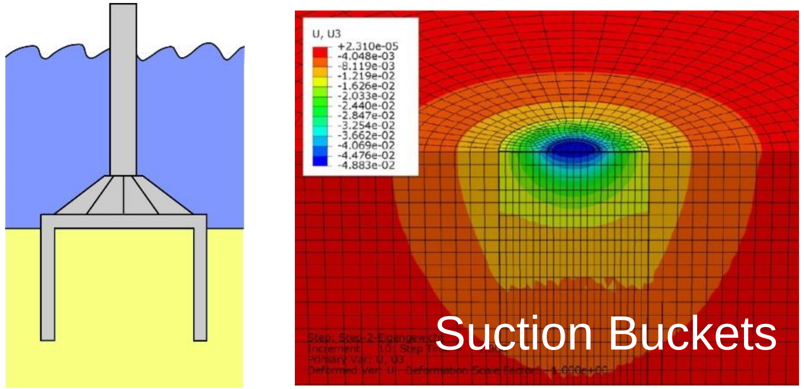
Calculation strategy

- Prediction of long-term deformations for arbitrary types of foundations
- Study of the whole soil-structure interaction under high-cyclic loading is possible









1. High-cycle accumulation model

Equations

Niemunis et al. (2005)

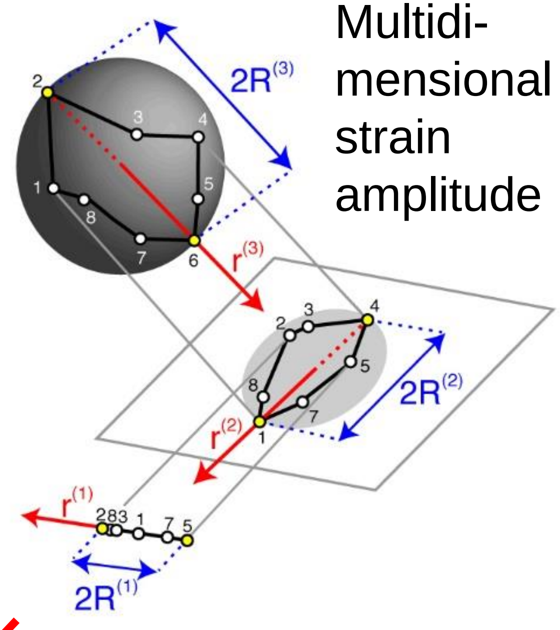
$$\dot{\boldsymbol{\sigma}} = \mathrm{E} : (\dot{\boldsymbol{\varepsilon}} - \dot{\boldsymbol{\varepsilon}}^{\mathrm{acc}} - \dot{\boldsymbol{\varepsilon}}^{\mathrm{pl}})$$

$\dot{\boldsymbol{\sigma}}$ = Stress rate (trend of stress)
E = Elastic stiffness (stress-dependent)
$\dot{\boldsymbol{\varepsilon}}$ = Strain rate (trend of strain)
$\dot{\boldsymbol{\varepsilon}}^{\mathrm{acc}}$ = Accumulation rate (prescribed)
$\dot{\boldsymbol{\varepsilon}}^{\mathrm{pl}}$ = Plastic strain rate (for stress paths that reach the yield surface during the cycles)

$$\dot{\boldsymbol{\varepsilon}}^{\mathrm{acc}} = \dot{\varepsilon}^{\mathrm{acc}}\, \mathbf{m}$$

$\mathbf{m}$ = Direction of accumulation (unit tensor)
$\dot{\varepsilon}^{\mathrm{acc}}$ = Intensity of accumulation (scalar)

$$\dot{\varepsilon}^{\mathrm{acc}} = f_{\mathrm{ampl}} \cdot \dot{f}_N \cdot f_p \cdot f_Y \cdot f_e$$

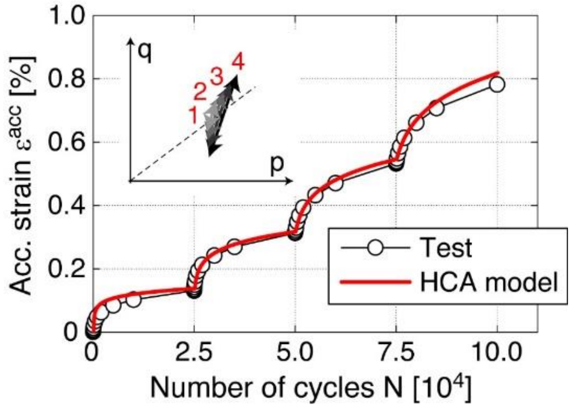


Multidimensional strain amplitude

Functions consider:

f_{ampl} = Strain amplitude
$\dot{f}_N$ = Cyclic preloading
f_p = Average mean pressure
f_Y = Average stress ratio
f_e = Void ratio

Preloading variable:



Direction: Wichtmann & Triantafyllidis (2017)
Multidimensional: Wichtmann & Knittel (2019)
Packages of cycles: Wichtmann et al. (2017)

1. High-cycle accumulation model

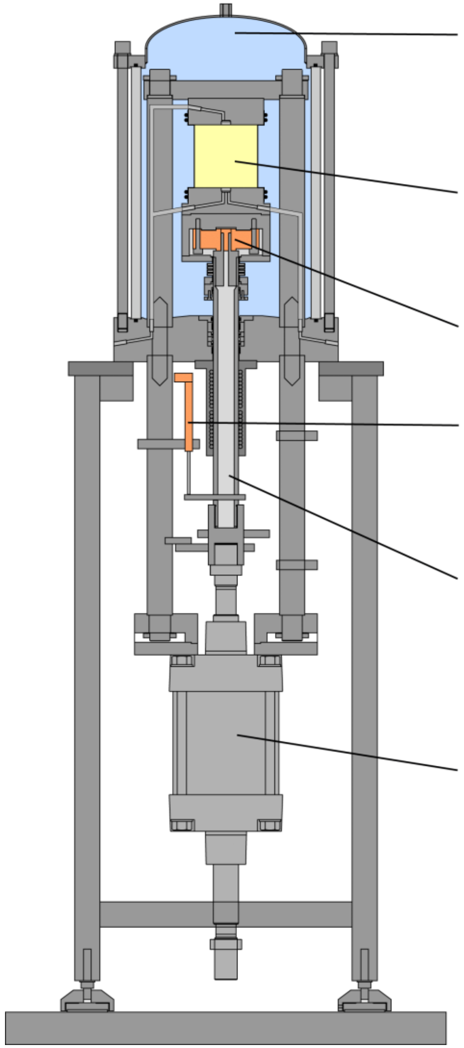
Equations

Influencing parameter	Function	Parameter
Strain amplitude $\varepsilon^{\mathrm{ampl}}$	$f_{\mathrm{ampl}} = \left(\frac{\varepsilon^{\mathrm{ampl}}}{10^{-4}}\right)^{C_{\mathrm{ampl}}}$	C_{ampl}
Void ratio e	$f_e = \frac{(C_e - e)^2}{1+e} \frac{1+e_{\max}}{(C_e - e_{\max})^2}$	C_e
Average eff. mean stress p^{av}	$f_p = \exp\left[-C_p \left(\frac{p^{\mathrm{av}}}{100\ \mathrm{kPa}} - 1\right)\right]$	C_p
Average stress ratio Y^{av}	$f_Y = \exp(C_Y\ \bar{Y}^{\mathrm{av}})$	C_Y
Cyclic preloading	$f_N = C_{N1}\ [\ln(1 + C_{N2}\ N) + C_{N3}\ N]$ $\dot{f}_N = C_{N1}\left[\frac{C_{N2}}{1 + C_{N2} N} + C_{N3}\right]$	C_{N1} C_{N2} C_{N3}

1. High-cycle accumulation (HCA) model

Calibration based on drained cyclic triaxial tests

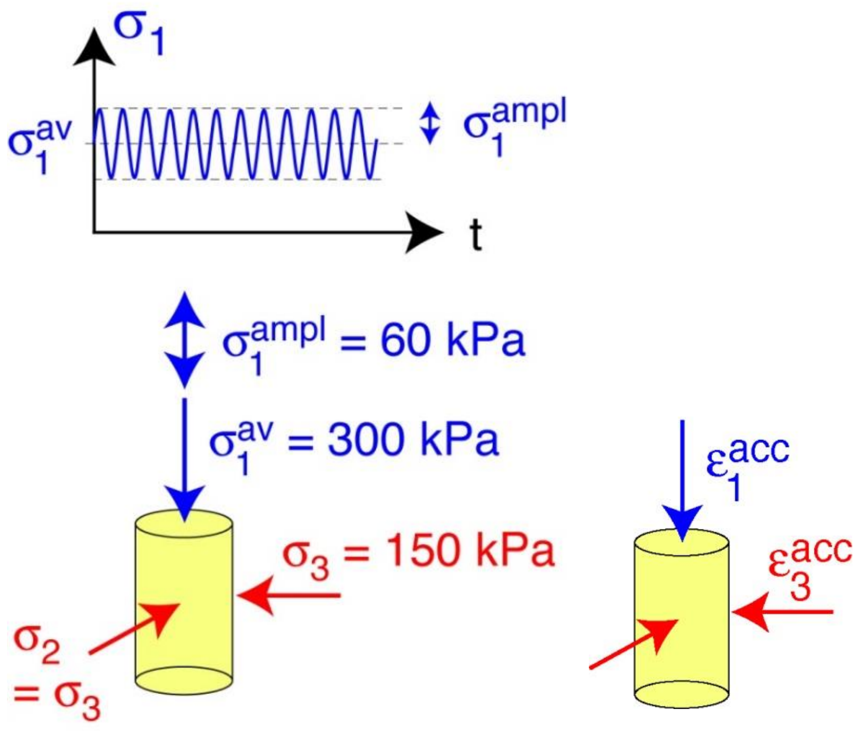
(New devices at RUB - Manufactured by Schudy Sondermaschinenbau)

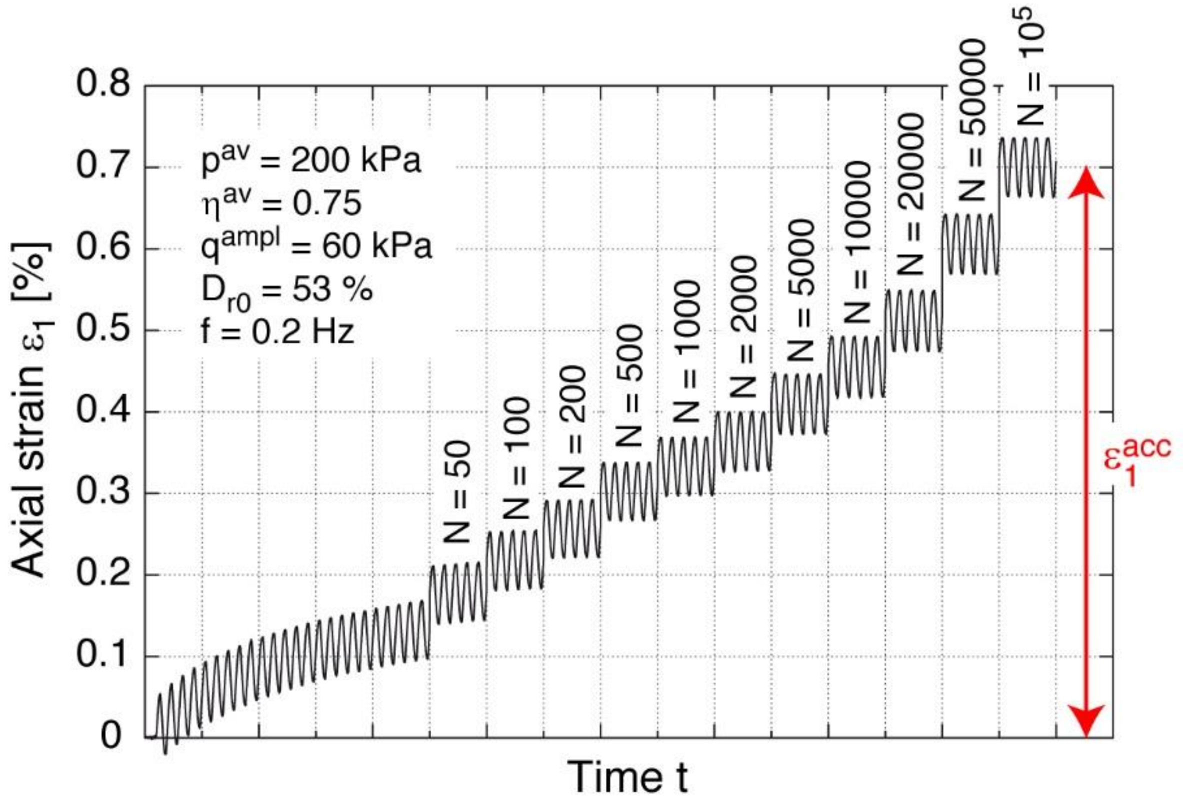


1. High-cycle accumulation model

Calibration based on laboratory tests

Result of a typical test on a medium dense sample of fine sand (relative density D_{r0} = 53 %)



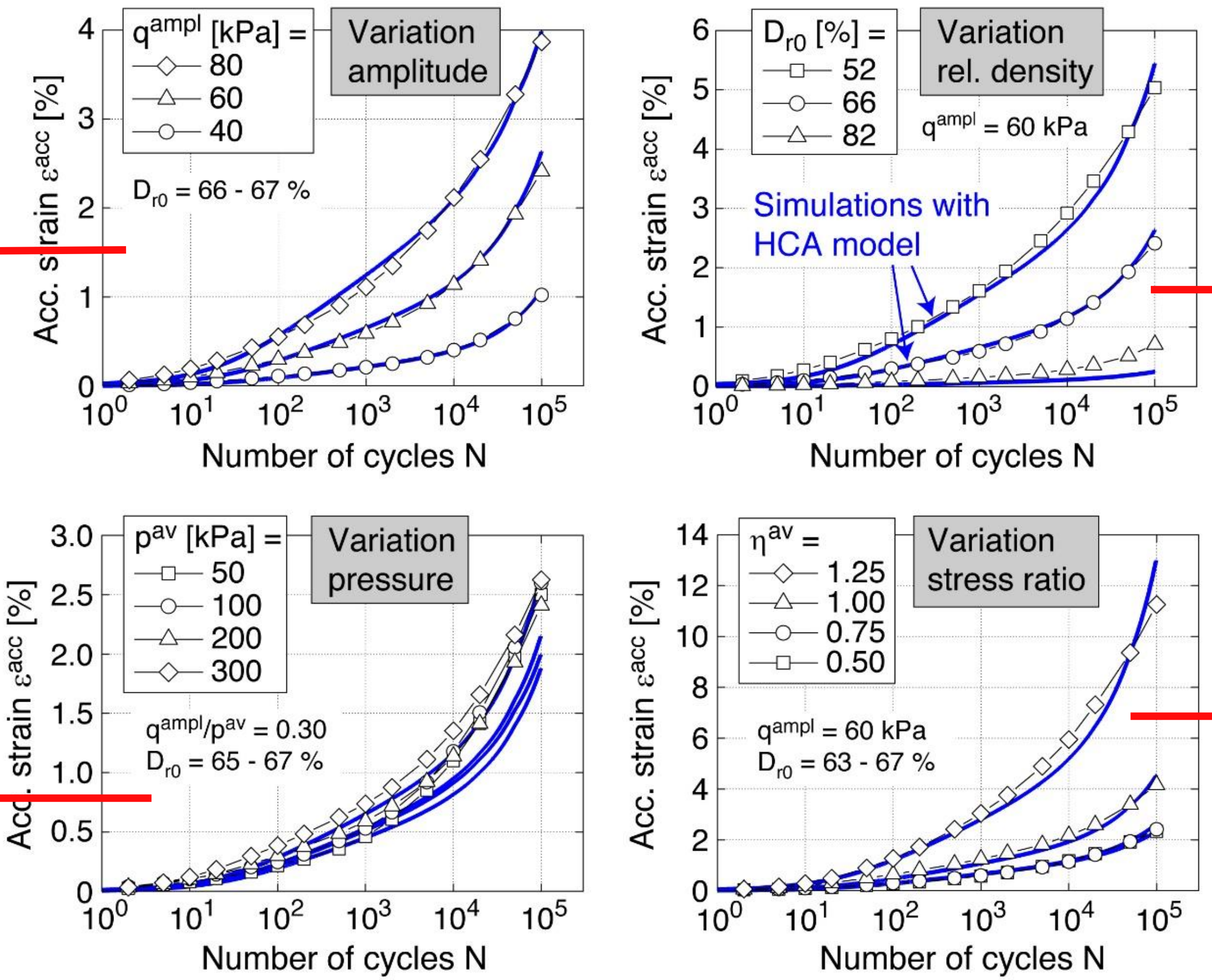


σ = effective stress

1. High-cycle accumulation model

Calibration based on cyclic triaxial tests

Wichtmann et al. (2010, 2015)



C_{ampl}

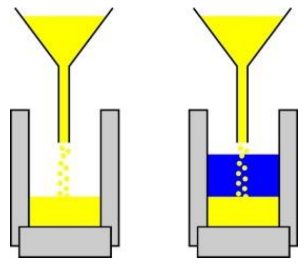
C_e

C_p

C_Y

From all tests: C_{N1}, C_{N2}, C_{N3}

- Fabric / sample preparation method influences strain accumulation
- Should be chosen in accordance with depositional history of soil in the field



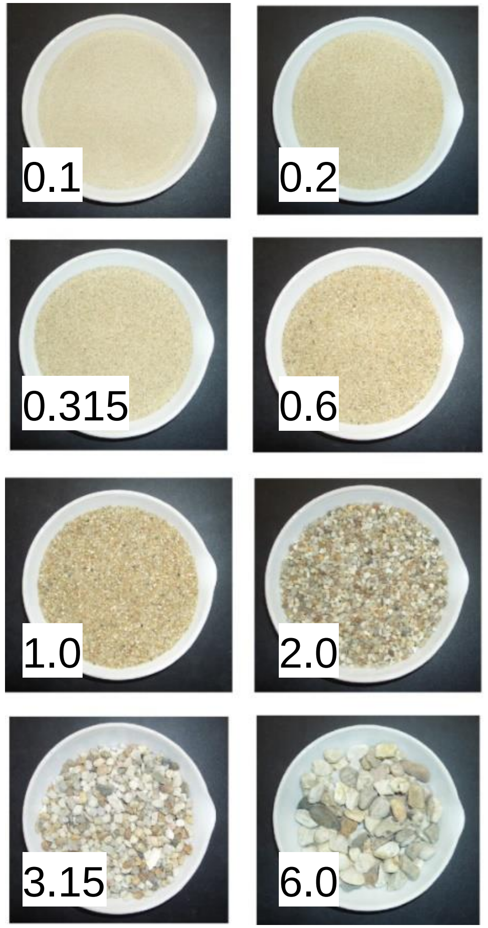
Wicht-mann et al. (2020)

$$\varepsilon^{acc} = \|\boldsymbol{\varepsilon}^{acc}\| = \sqrt{(\varepsilon_1^{acc})^2 + 2 \cdot (\varepsilon_3^{acc})^2}$$

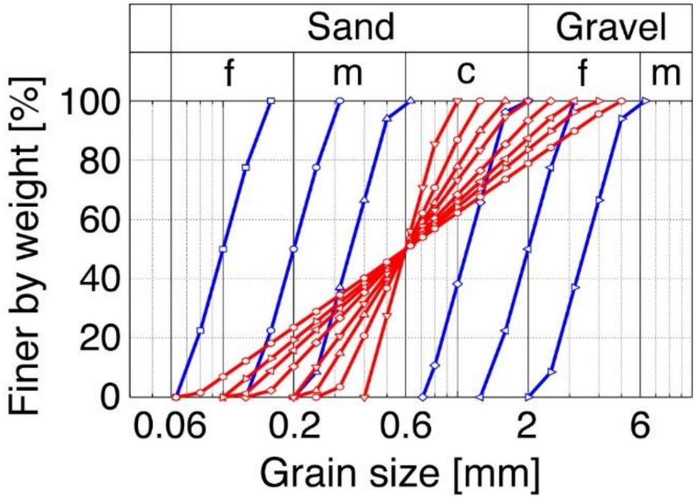
1. High-cycle accumulation model

Simplified calibration procedure

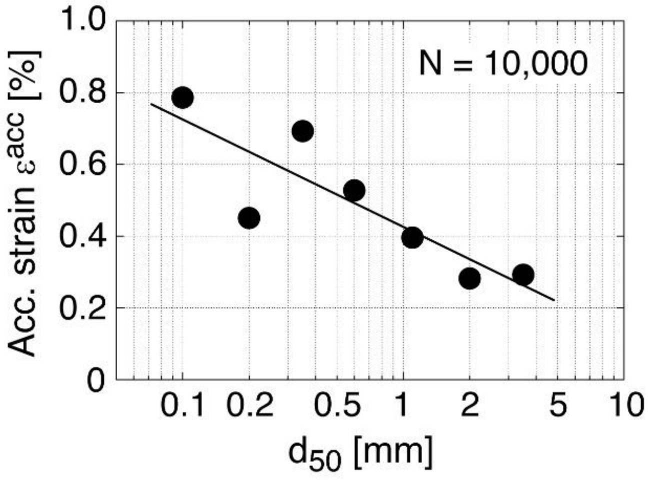
Wichtmann et al. (2009, 2015)

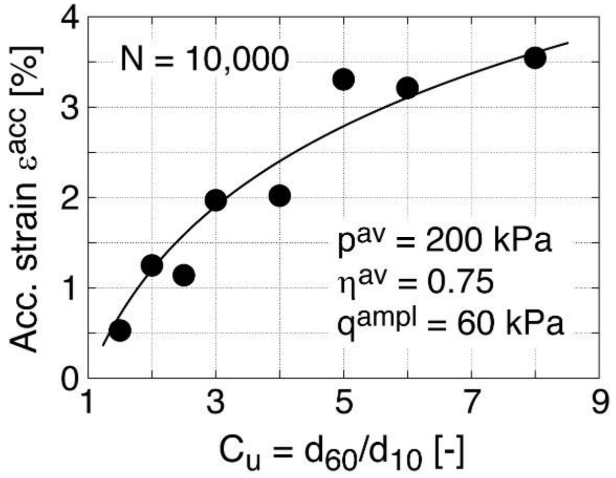


(d_{50} [mm])



- Approx. 350 drained cyclic triaxial tests on 22 quartz sand mixtures with mean grain sizes $0.1\text{ mm} \leq d_{50} \leq 3.5\text{ mm}$ and uniformity coefficients $1.5 \leq C_u \leq 8$



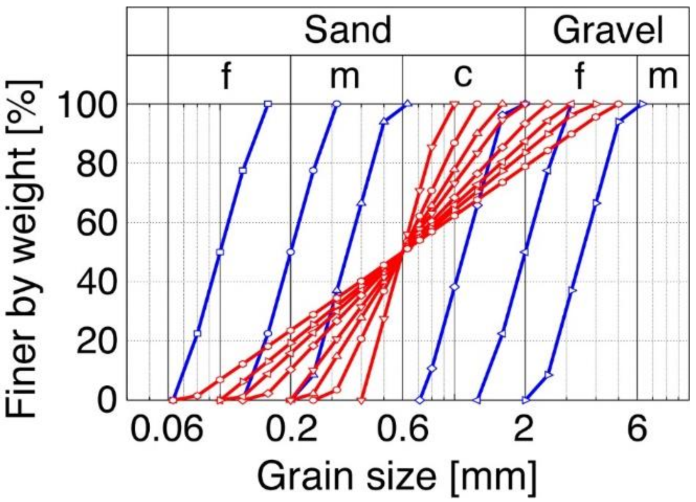


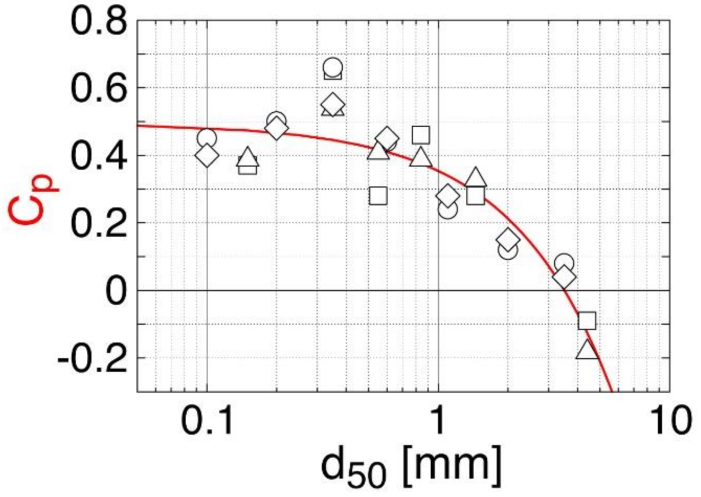
- ε^{acc} decreases with d_{50} and increases with C_u

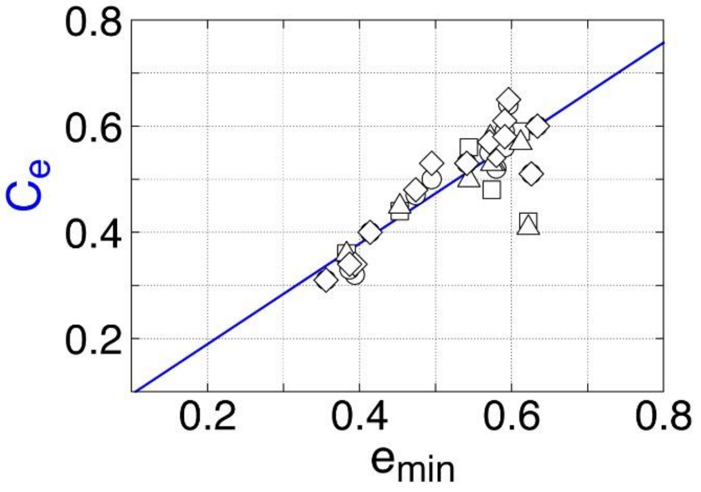
1. High-cycle accumulation model

Simplified calibration procedure

Wichtmann et al. (2015)







$$C_p = 0.41 \cdot [1 - 0.34 \cdot (d_{50}[\mathrm{mm}] - 0.6)]$$

$$C_e = 0.95 \cdot e_{\min}$$

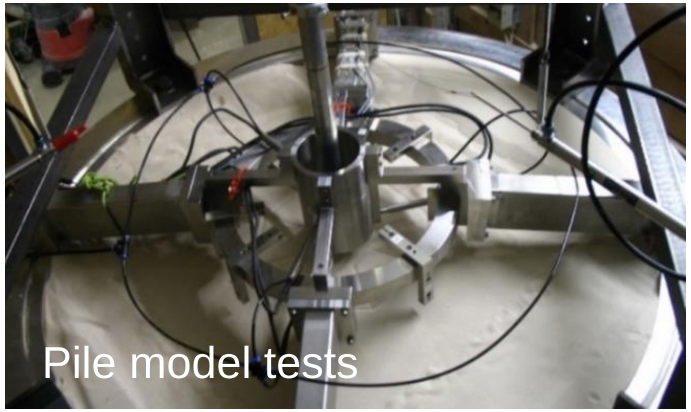
- Determination of all parameters from correlations only for rough estimates
- Recommended minimum standard:

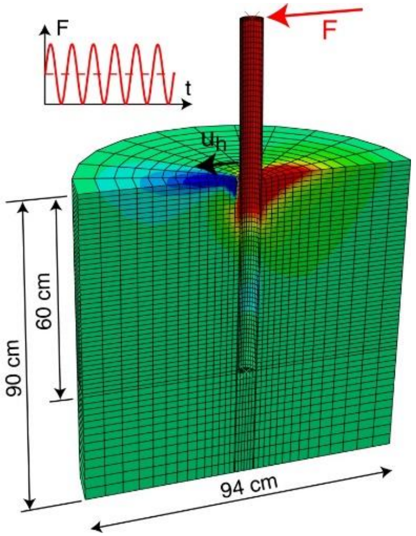
  C_{ampl}, C_e, C_p, C_Y from correlations, C_{N1}, C_{N2}, C_{N3} from a single cyclic test

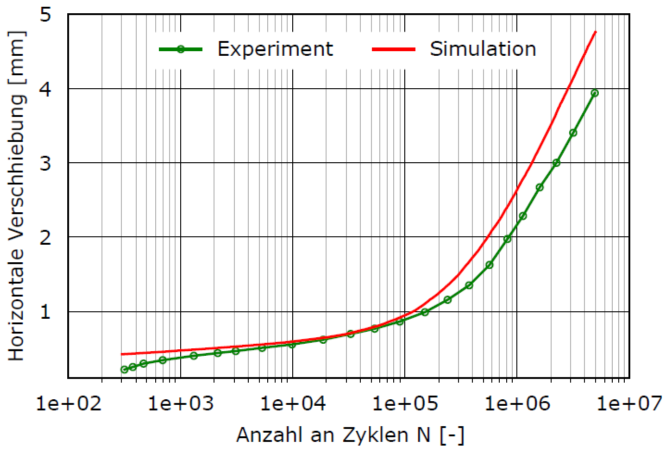
Grain shape, shell fragments, fines content:
Wichtmann (2016)
Wichtmann et al. (2019, 2020)

2. Validation of HCA model

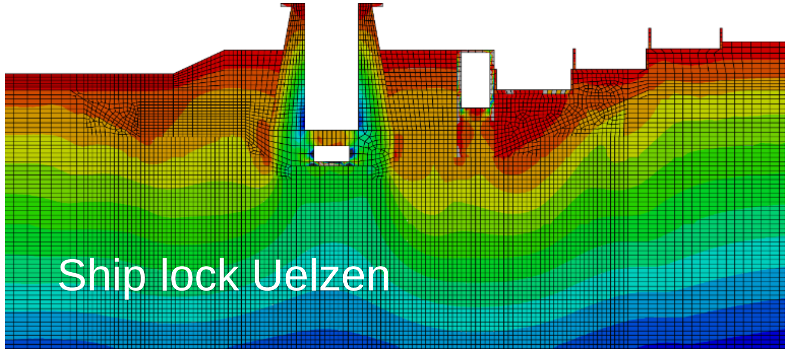
Back-analysis of model tests or measurements at real buildings

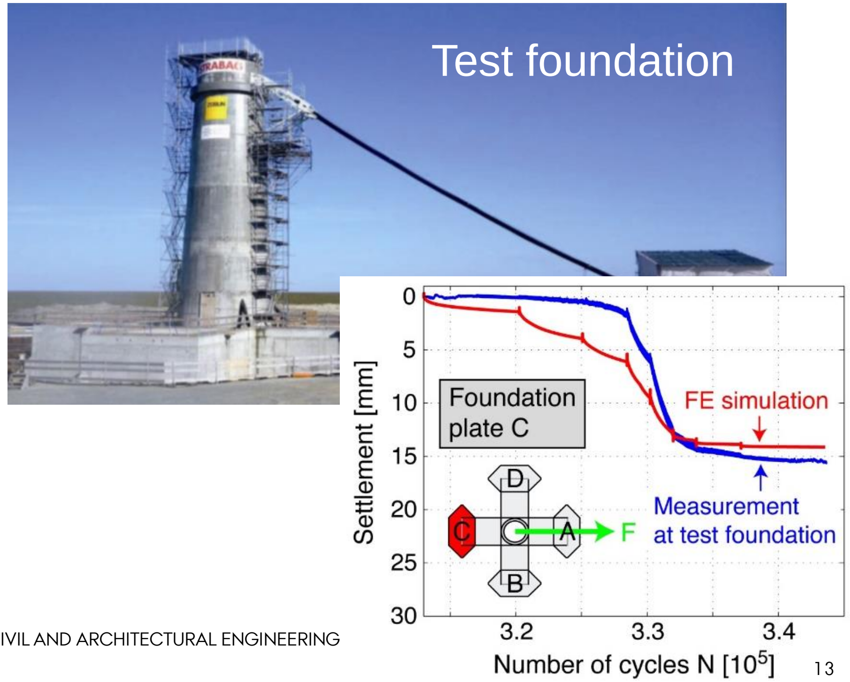






Zachert (2015)
Zachert et al. (2020)
Machacek et al. (2018)
Wichtmann et al. (2019e)
Staubach et al. (2021e)
Staubach (2022)



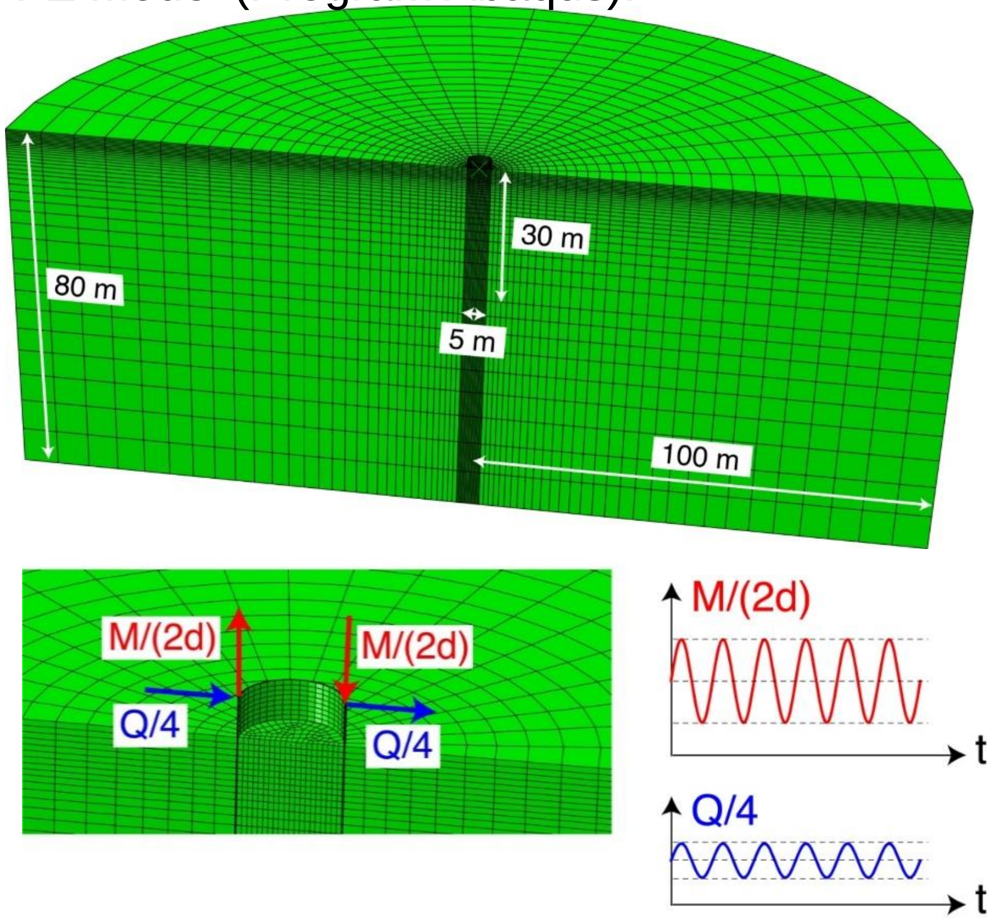


3. Application of HCA model to OWT monopile foundations

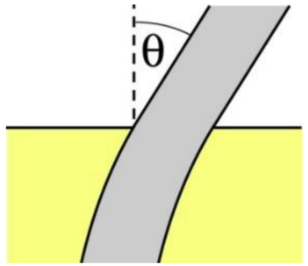
Influence of soil state and loading

Staubach & Wichtmann (2020)

FE model (Program Abaqus):

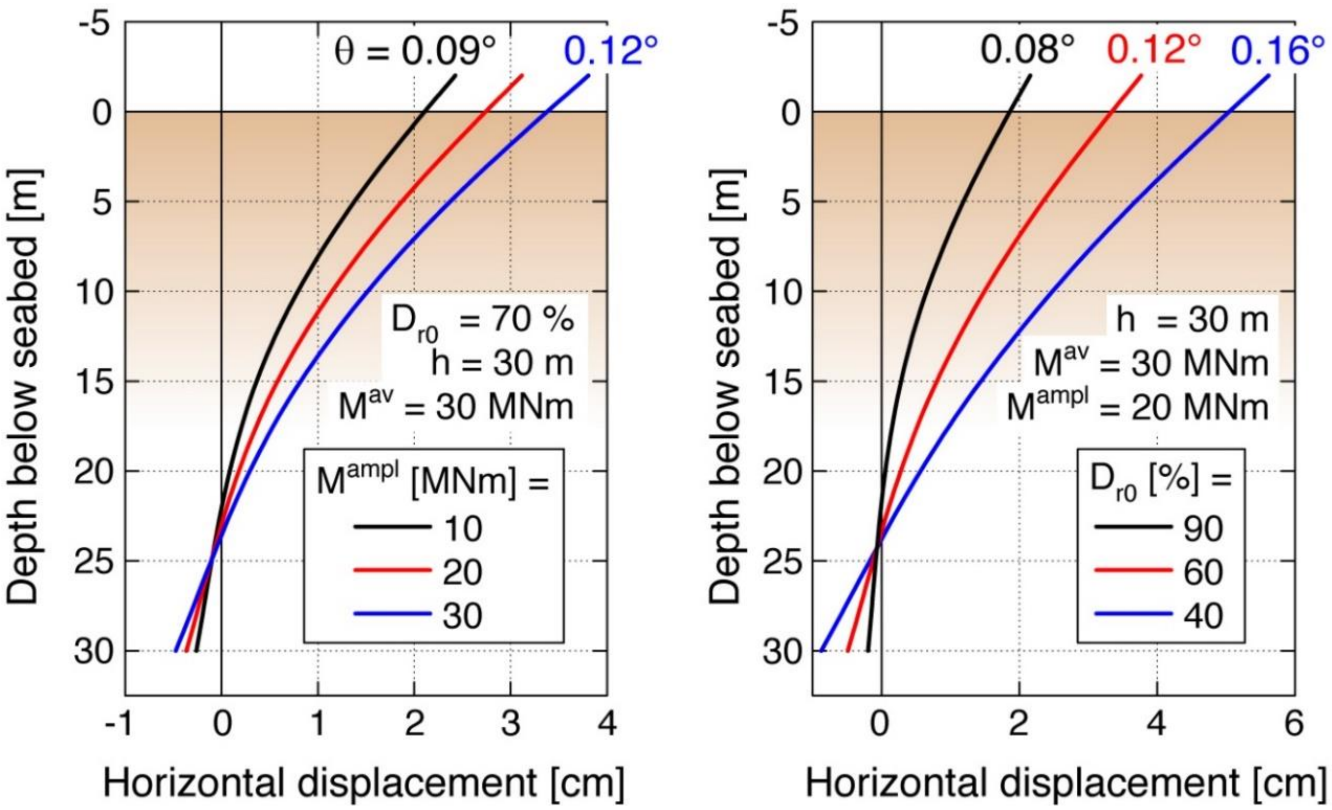


N = 10^6 cycles



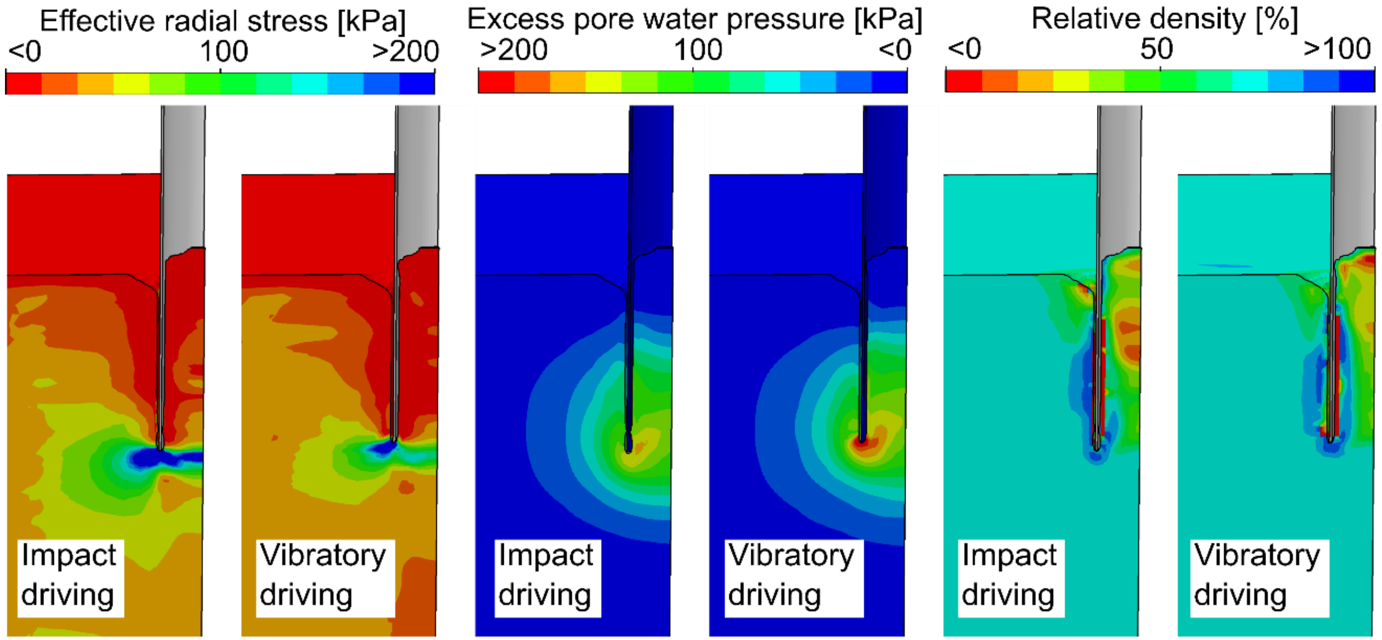
Variation of load amplitude:

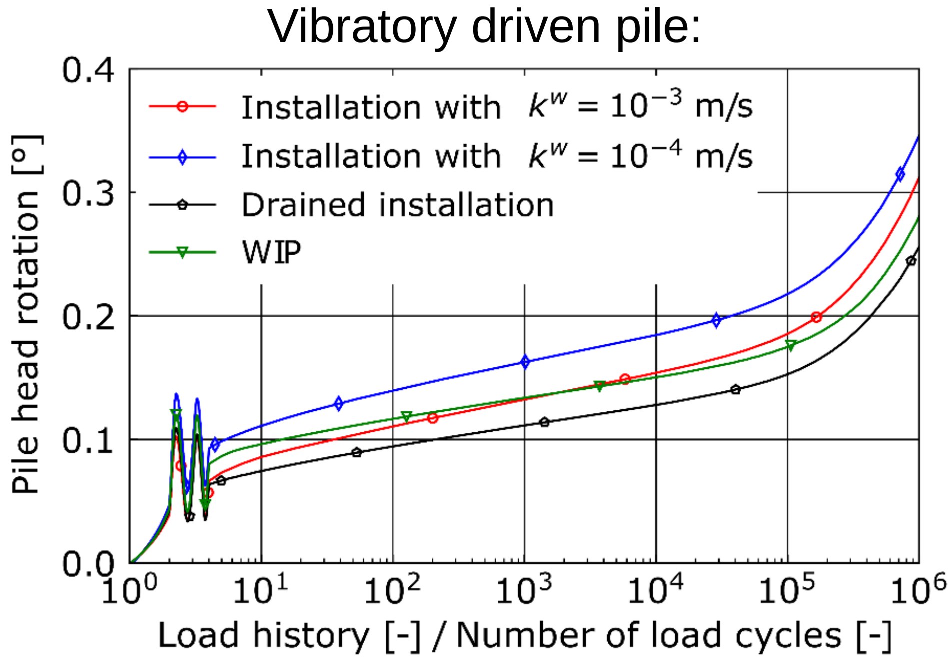
Variation of soil density:



3. Application of HCA model to OWT monopile foundations

Installation effects



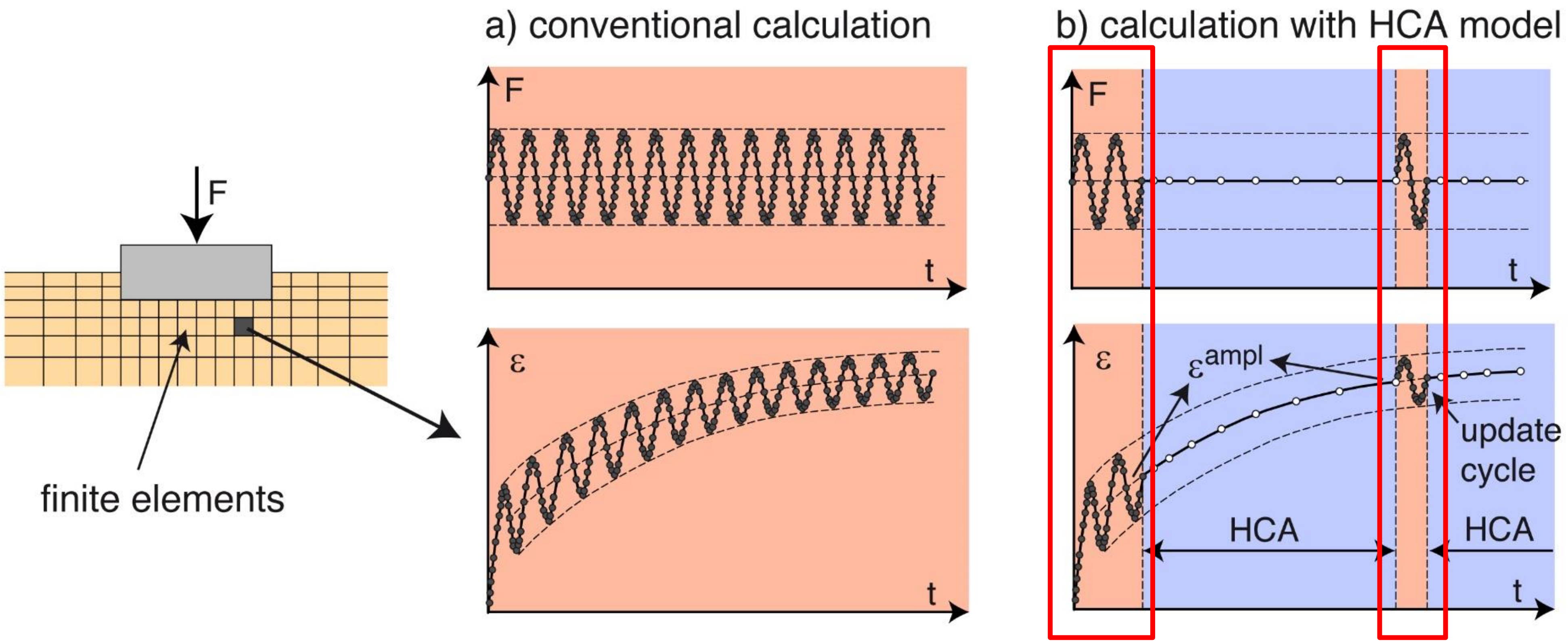


Staubach (2022, PhD thesis), Staubach et al. (2020, 2021a, 2021b, 2021c, 2022c)

- Pile installation changes density and stress and thus influences long-term deformations
- Pile installation effects depend on drainage conditions
- Assuming wished-in-place conditions may not always be conservative

3. Application of HCA model to OWT monopile foundations

Influence of the constitutive model used in combination with HCA model



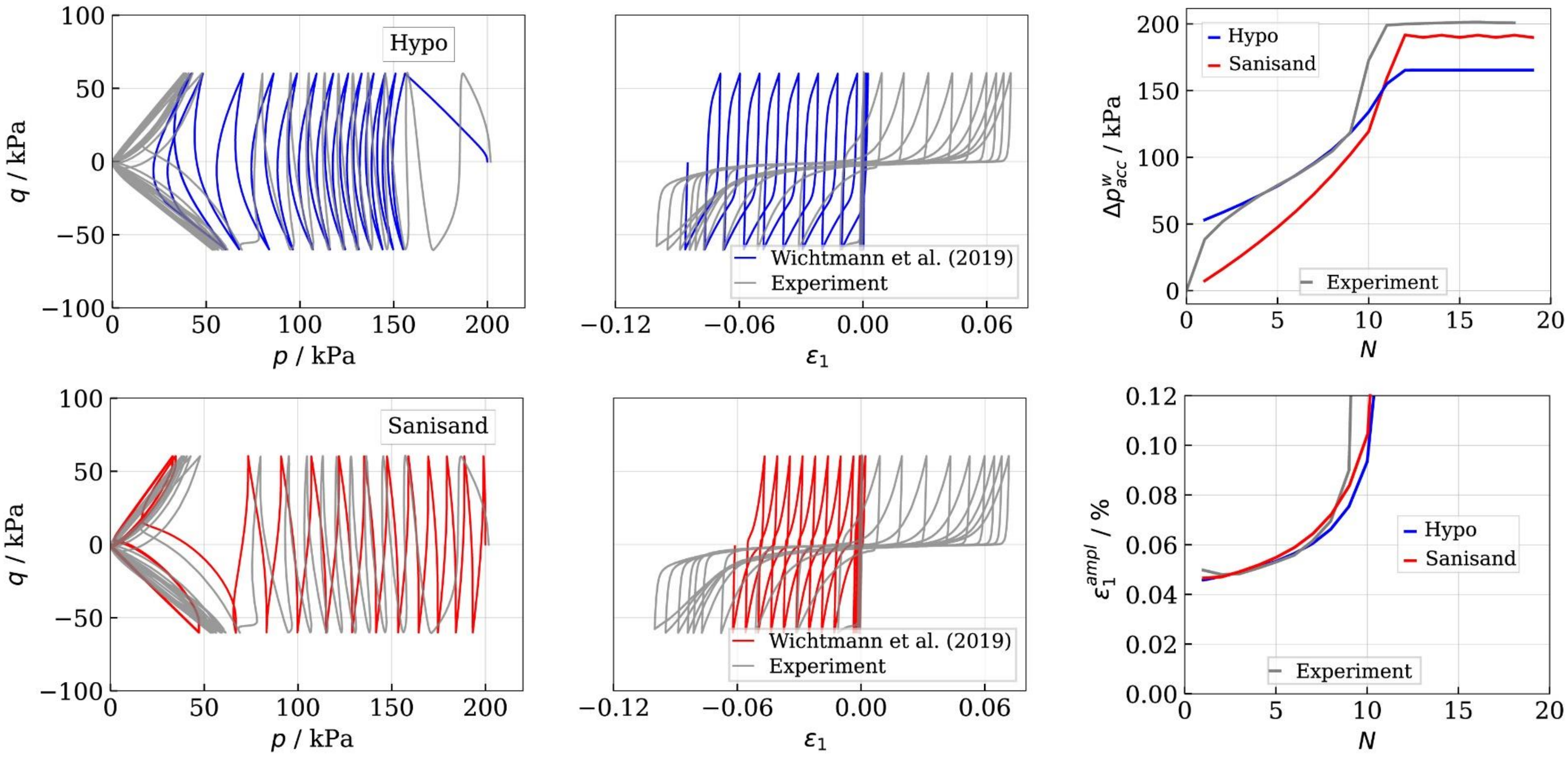
- Which conventional constitutive model to use for the first two and update cycles?
- Comparative study with two popular models: Hypoplasticity with intergranular strain (von Wolffersdorff 1996, Niemunis & Herle 1994) and Sanisand (Dafalias & Manzari 2004)

3. Application of HCA model to OWT monopile foundations

Influence of the constitutive model used in combination with HCA model

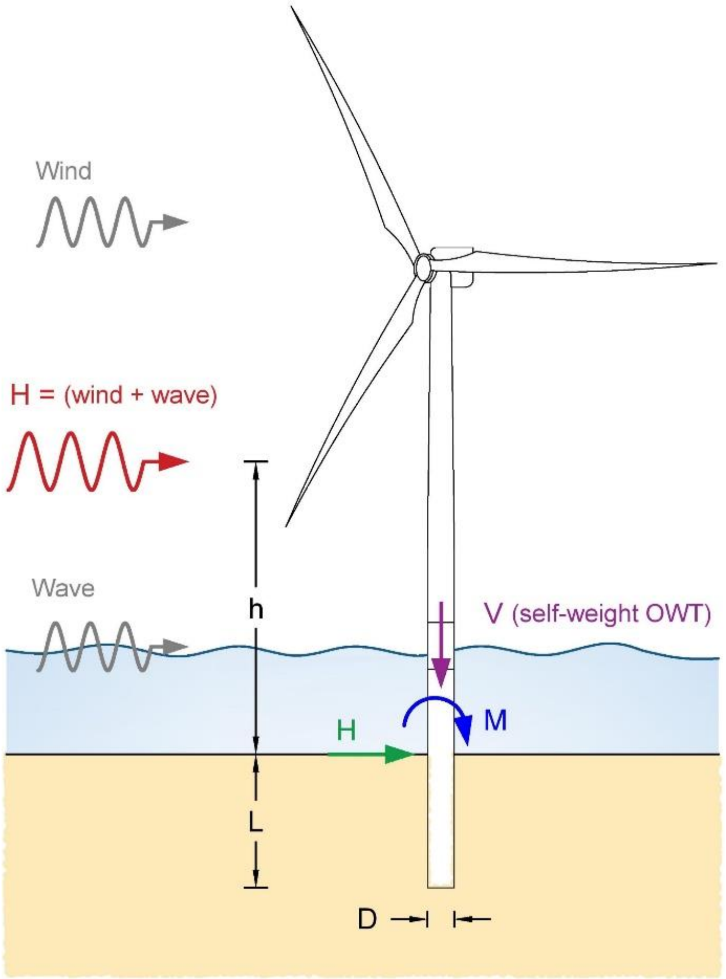
Wichtmann, T., Fuentes, W., Triantafyllidis, Th. (2019): Inspection of three sophisticated constitutive models based on monotonic and cyclic tests on fine sand: Hypoplasticity vs. Sanisand vs. ISA. Soil Dynamics and Earthquake Engineering, Vol. 124, pp. 172-183

Simulation of undrained cyclic triaxial test



3. Application of HCA model to OWT monopile foundations

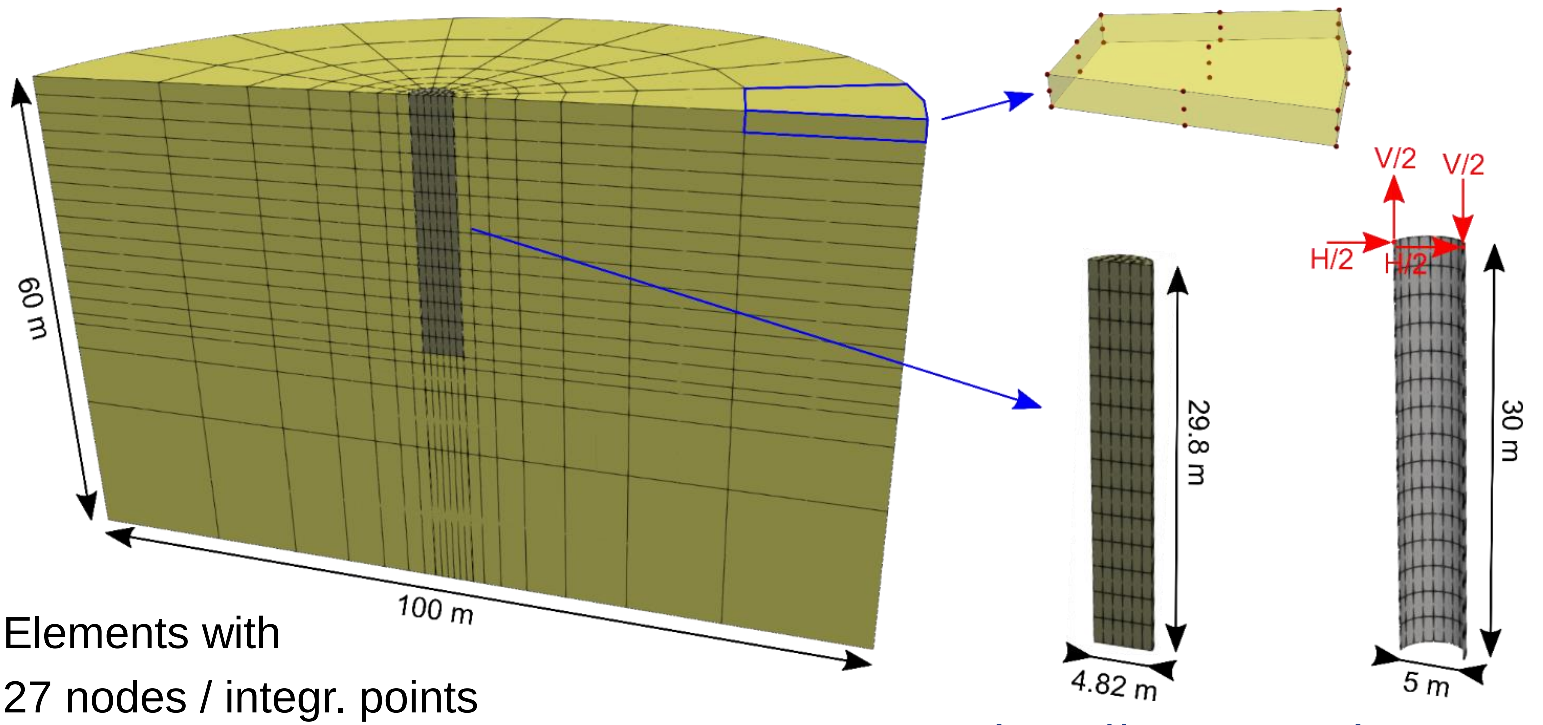
Influence of the constitutive model used in combination with HCA model



D = 5 m $\quad$ I_{D0} = 0,6 $\quad$ $M^{av} = M^{ampl}$ = 30 MNm

L = 30 m $\quad$ k = 10^{-4} m/s $\quad$ h = 20 m, f = 1 Hz

FE model (Program numgeo)



Elements with
27 nodes / integr. points

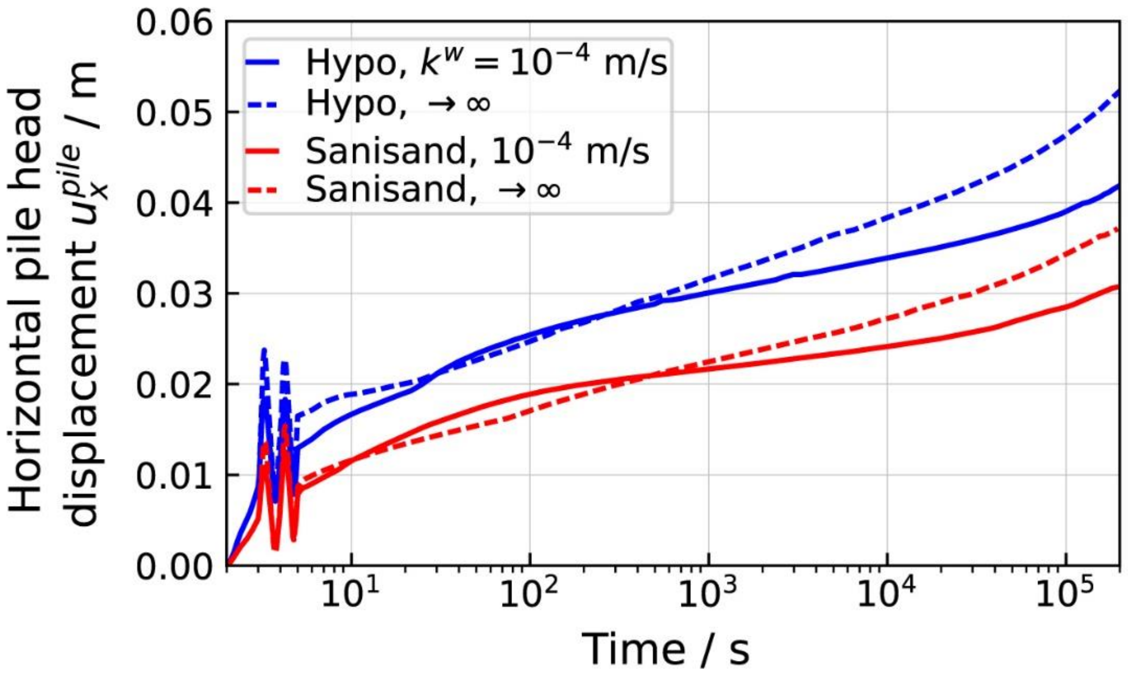
http://numgeo.de

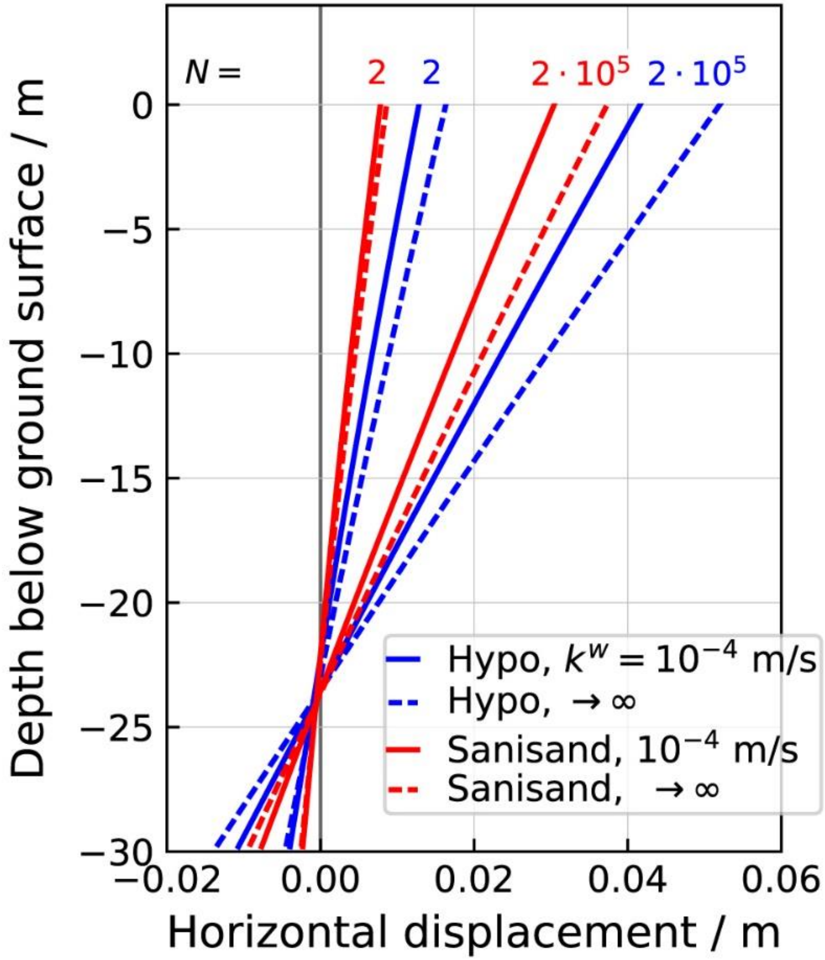
3. Application of HCA model to OWT monopile foundations

Influence of the constitutive model used in combination with HCA model

Variation of drainage conditions

- Fully drained ($k^w \rightarrow \infty$)
- Partially drained ($k^w = 10^{-4}$ m/s)

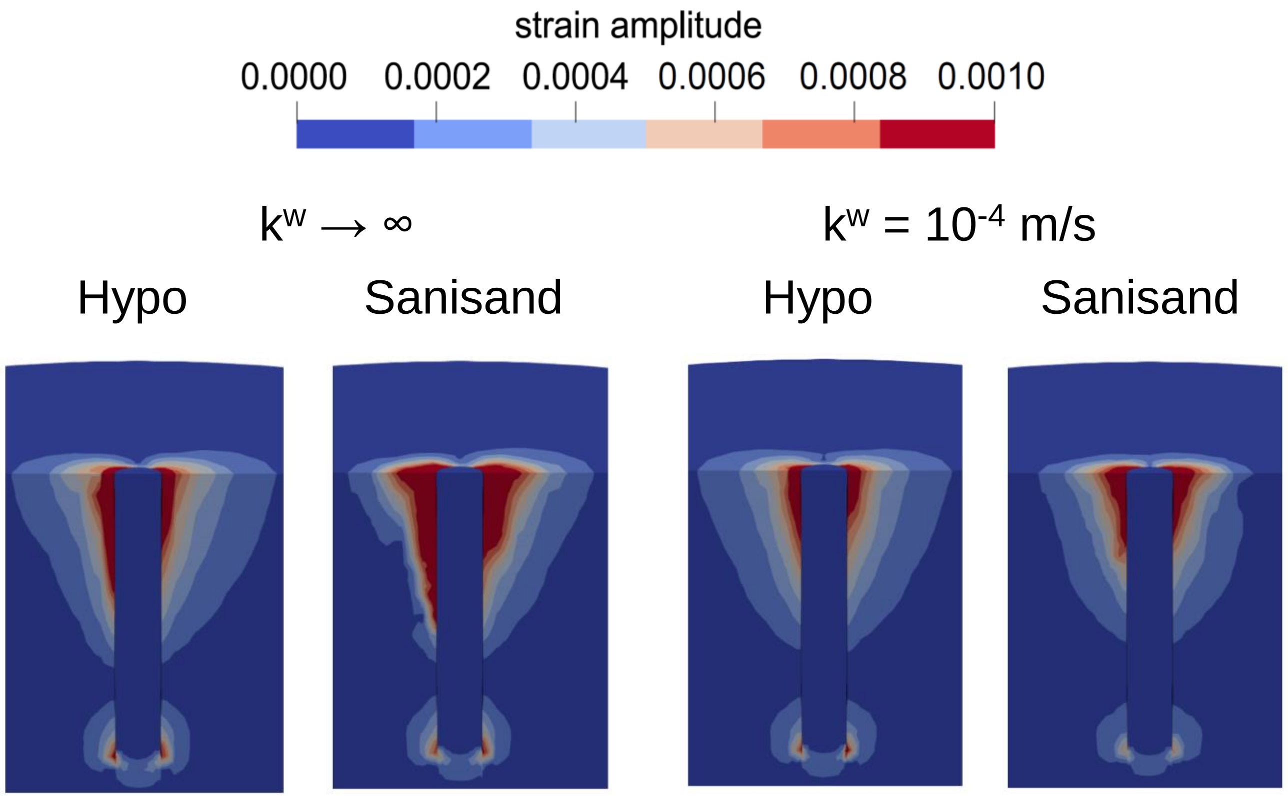




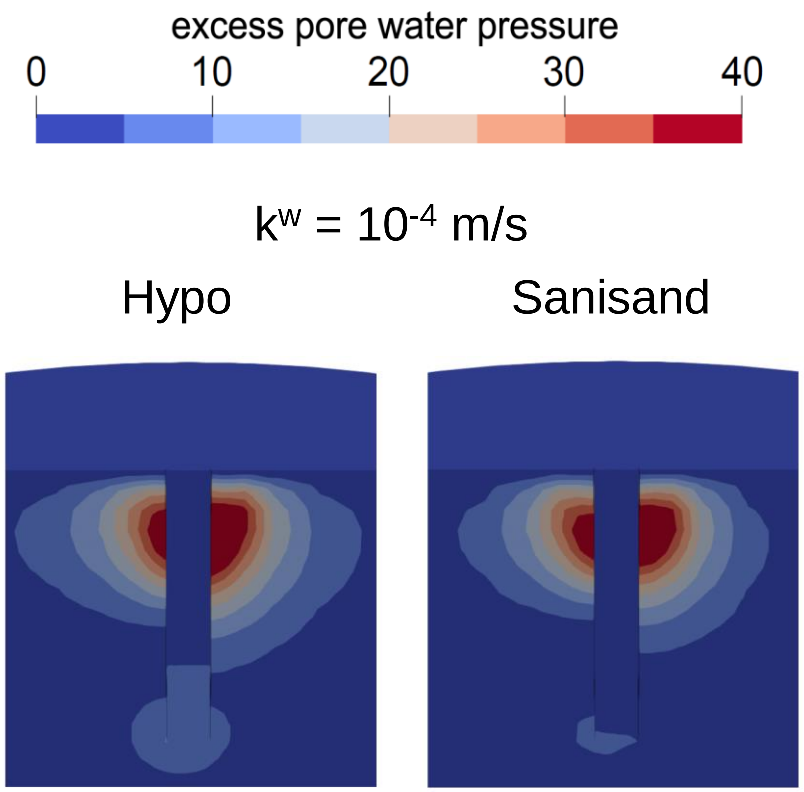
3. Application of HCA model to OWT monopile foundations

Influence of the constitutive model used in combination with HCA model

Strain amplitude (constant up to N = 2×10^5):



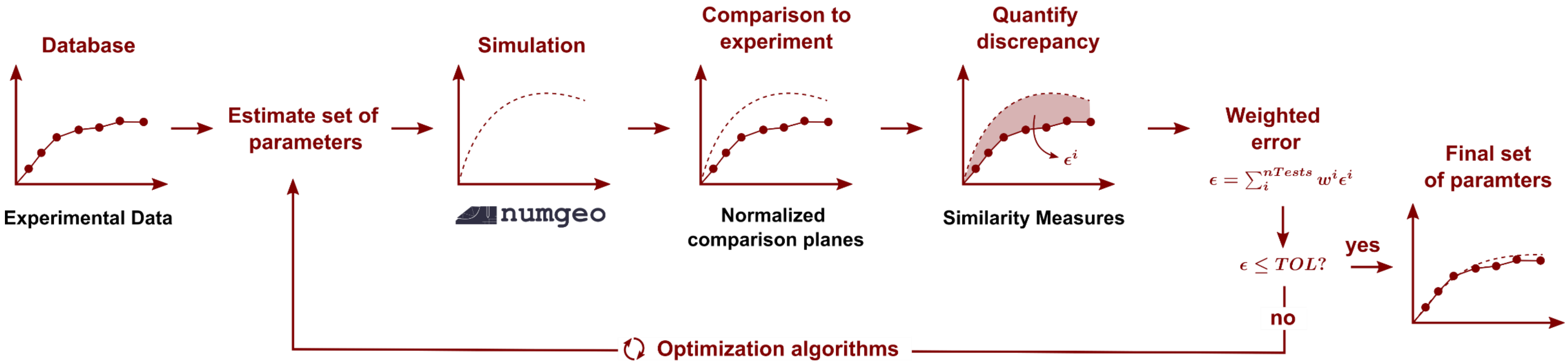
Time with maximum excess pore water pressure (N = 27):



3. Application of HCA model to OWT monopile foundations

Influence of calibration method

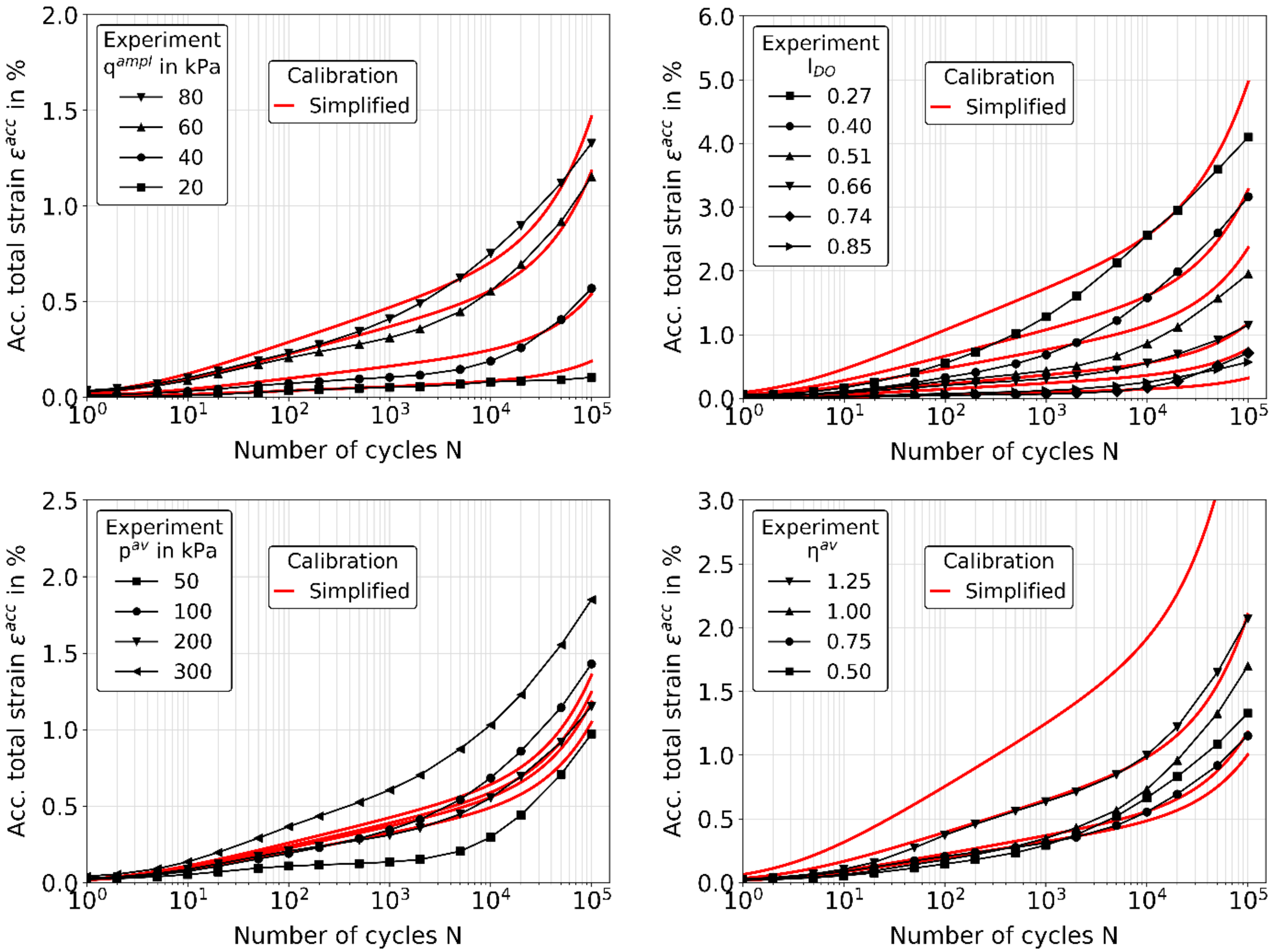
- Simplified calibration using correlations and determining C_{Ni} from a single cyclic test
- Calibration based on experiments, by-hand
- Calibration based on experiments, using an Automated Calibration Tool (ACT)



Machaček et al. (2022)

3. Application of HCA model to OWT monopile foundations

Influence of calibration method



Simplified calibration:

C_{ampl}, C_e, C_p, C_Y from correlations,

C_{Ni} from a single cyclic test

HCA model parameter set

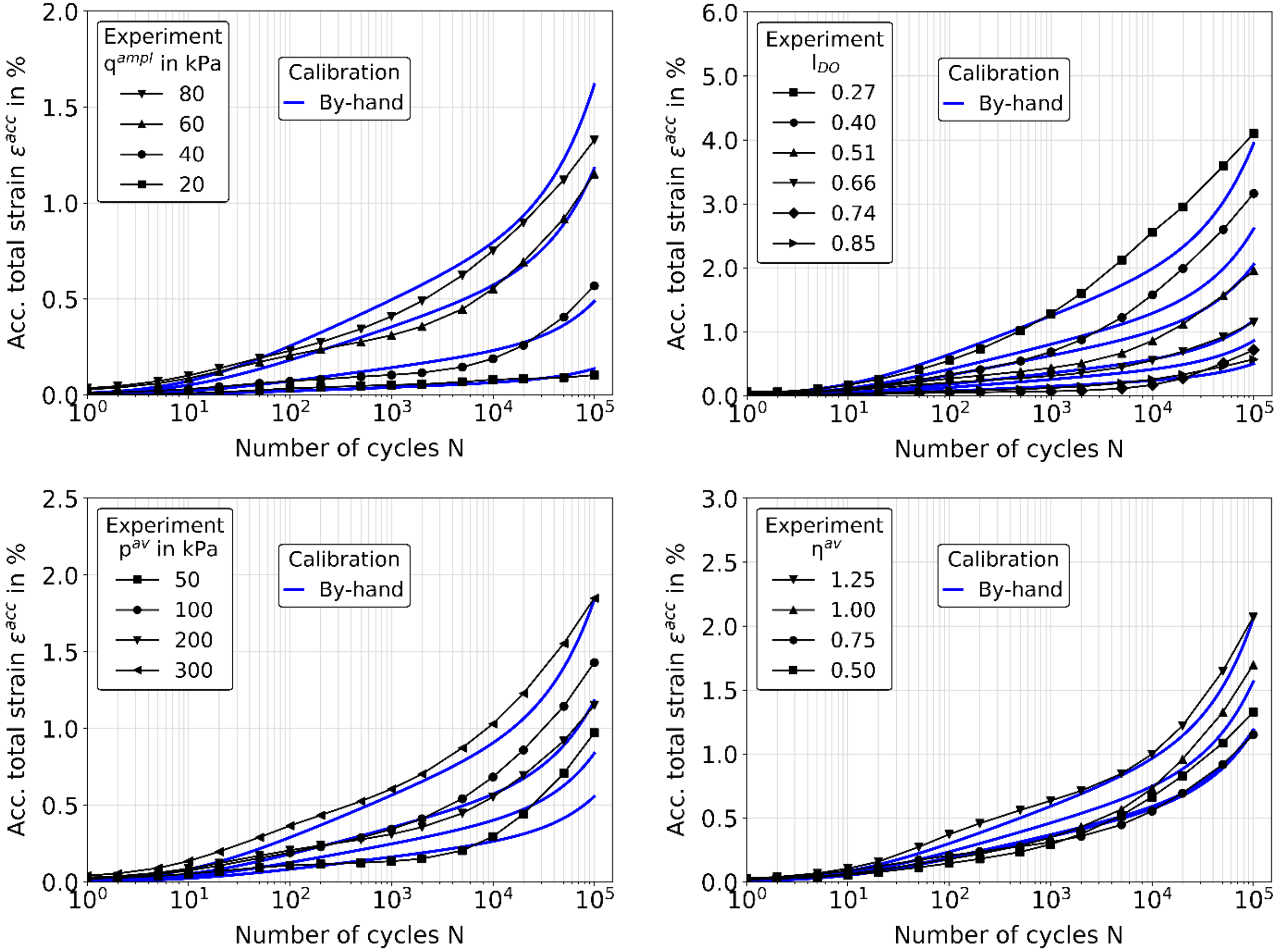
C_{ampl}	C_e	C_p	C_Y
1.70	0.50	0.46	2.31

$C_{N1}\ (10^{-4})$	C_{N2}	$C_{N3}\ (10^{-5})$
7.82	0.35	10.08

Cost function: 0.1074

3. Application of HCA model to OWT monopile foundations

Influence of calibration method



Calibration by hand using all available test data:

with additional optimization based on visual inspection of the element test simulation results

HCA model parameter set

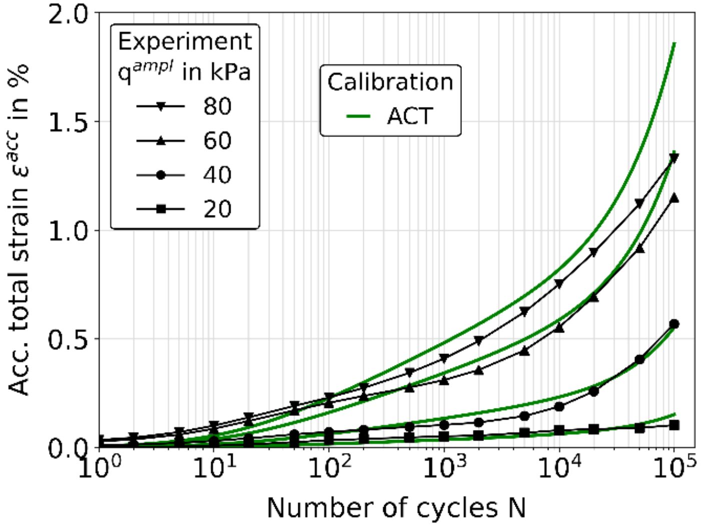
C_{ampl}	C_e	C_p	C_Y
1.93	0.45	0.11	1.24

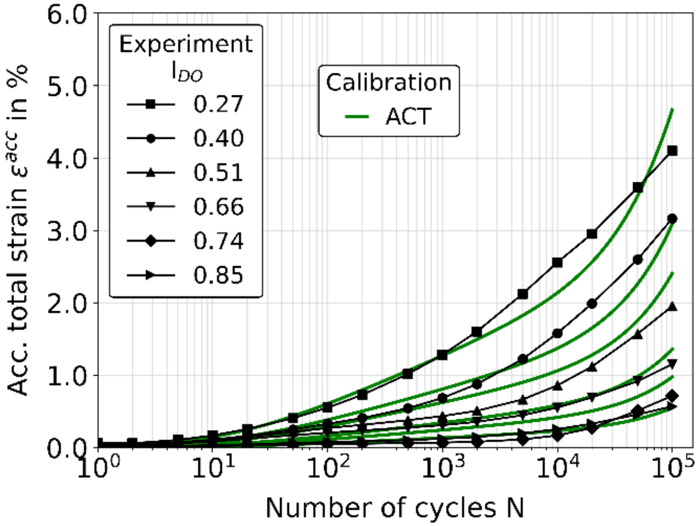
C_{N1} (10^{-4})	C_{N2}	C_{N3} (10^{-5})
4.85	0.093	7.50

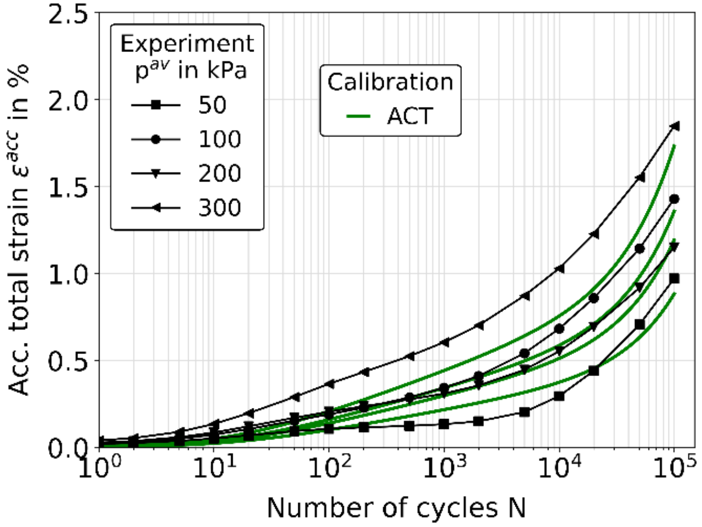
Cost function: 0.0763

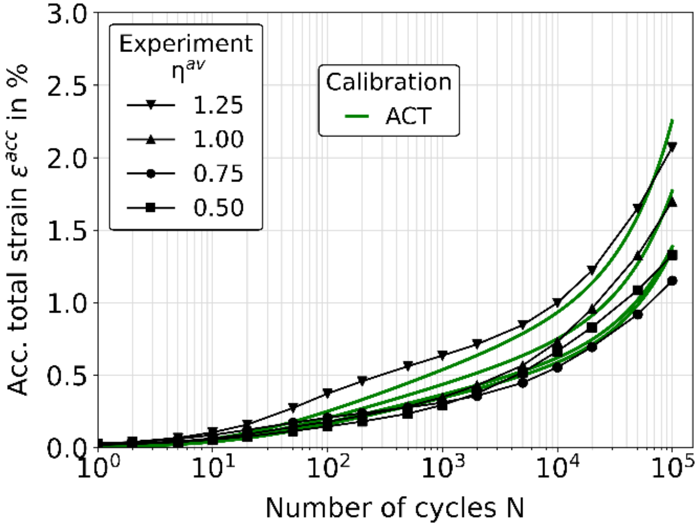
3. Application of HCA model to OWT monopile foundations

Influence of calibration method









Calibration with ACT using all available test data:

Optimization by Hybrid Quantum-behaved Particle Multi-Swarm Optimization (HQPMSO)

HCA model parameter set

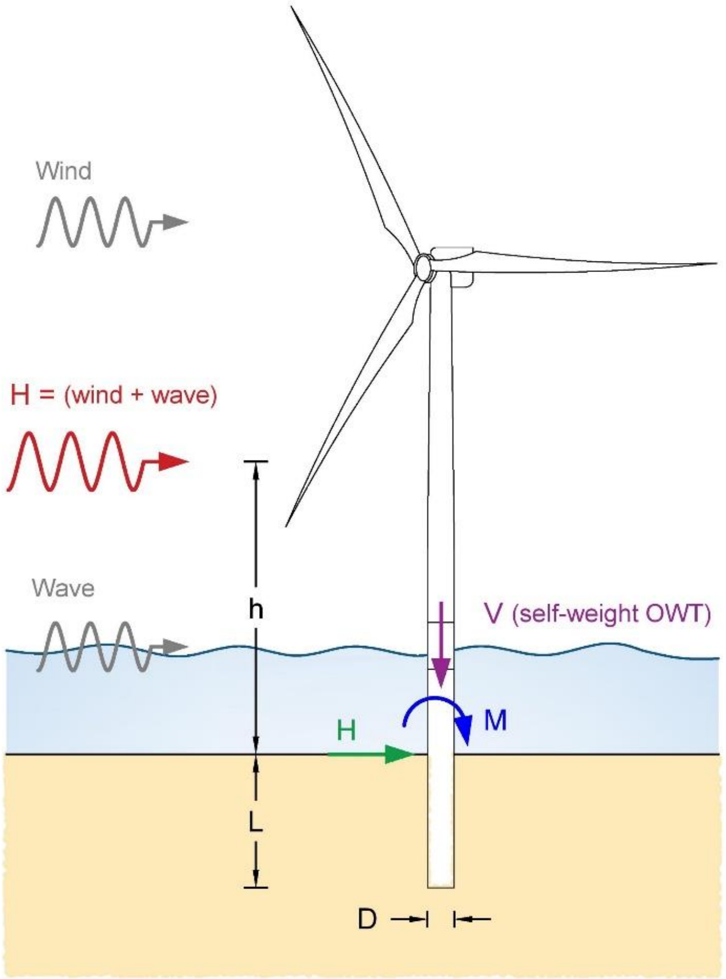
C_{ampl}	C_e	C_p	C_Y
1.98	0.46	0.34	1.15

C_{N1} (10^{-4})	C_{N2}	C_{N3} (10^{-5})
7.00	0.60	9.02

Cost function: 0.0671

3. Application of HCA model to OWT monopile foundations

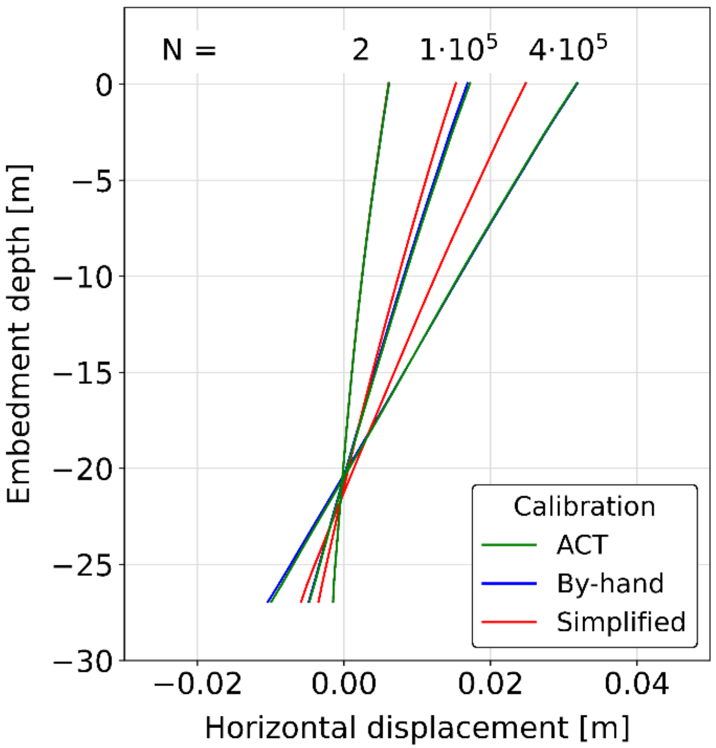
Influence of calibration method

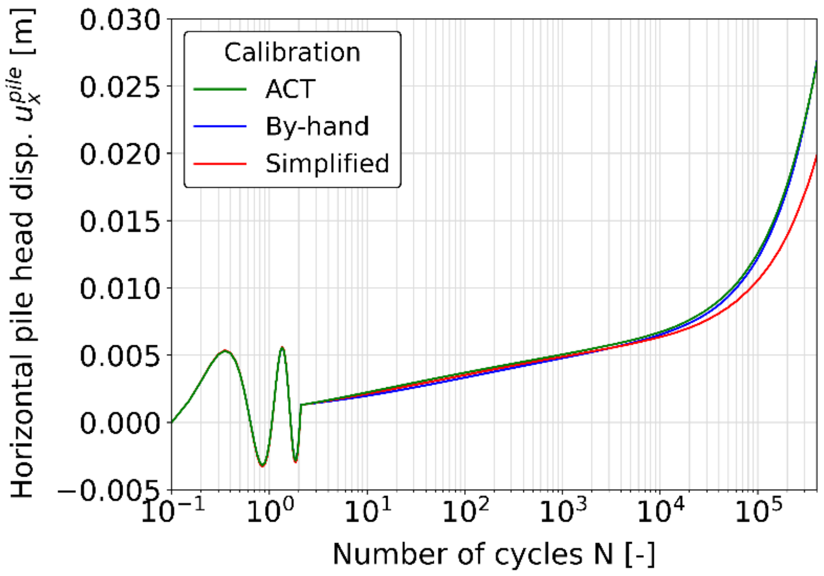


$V = 4$ MN

$D = 9$ m $I_{D0} = 0{,}6$ $M^{av} = M^{ampl} = 72$ MNm

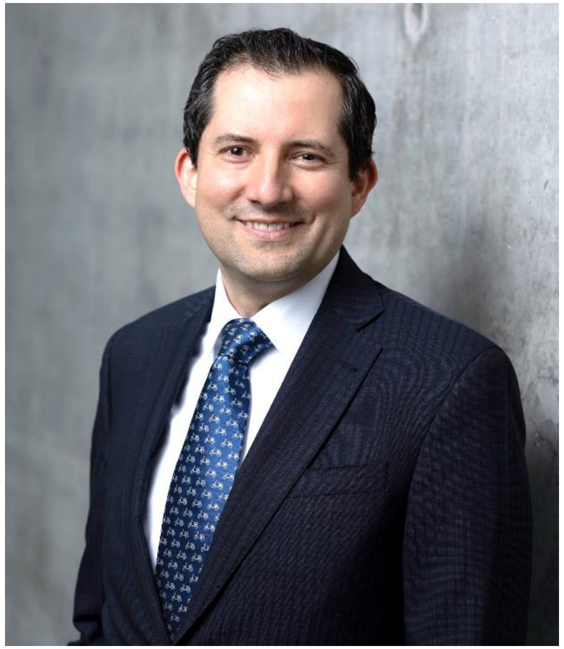
$L = 27$ m $k = 10^{-4}$ m/s $h = 60$ m, $f = 0.1$ Hz





4. Summary and conclusions

- High-cycle accumulation model (HCA) is formulated based on extensive experimental studies
- Calibration based on drained cyclic triaxial tests or following a simplified procedures applying correlations with the grain size distribution curve
- Validation of HCA model by recalculations of element, model and field tests
- Application of the HCA model to OWT monopile foundations shows influence of
  - Chosen calibration method
  - Conventional constitutive model coupled with HCA model
- Ongoing investigations
  - New calibration method based on cyclic simple shear tests
  - Amplitude and strain rate effects on clayey materials



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