Karlsruher Institut für Technologie

Advances in modeling the long-term behavior of offshore wind turbine foundations

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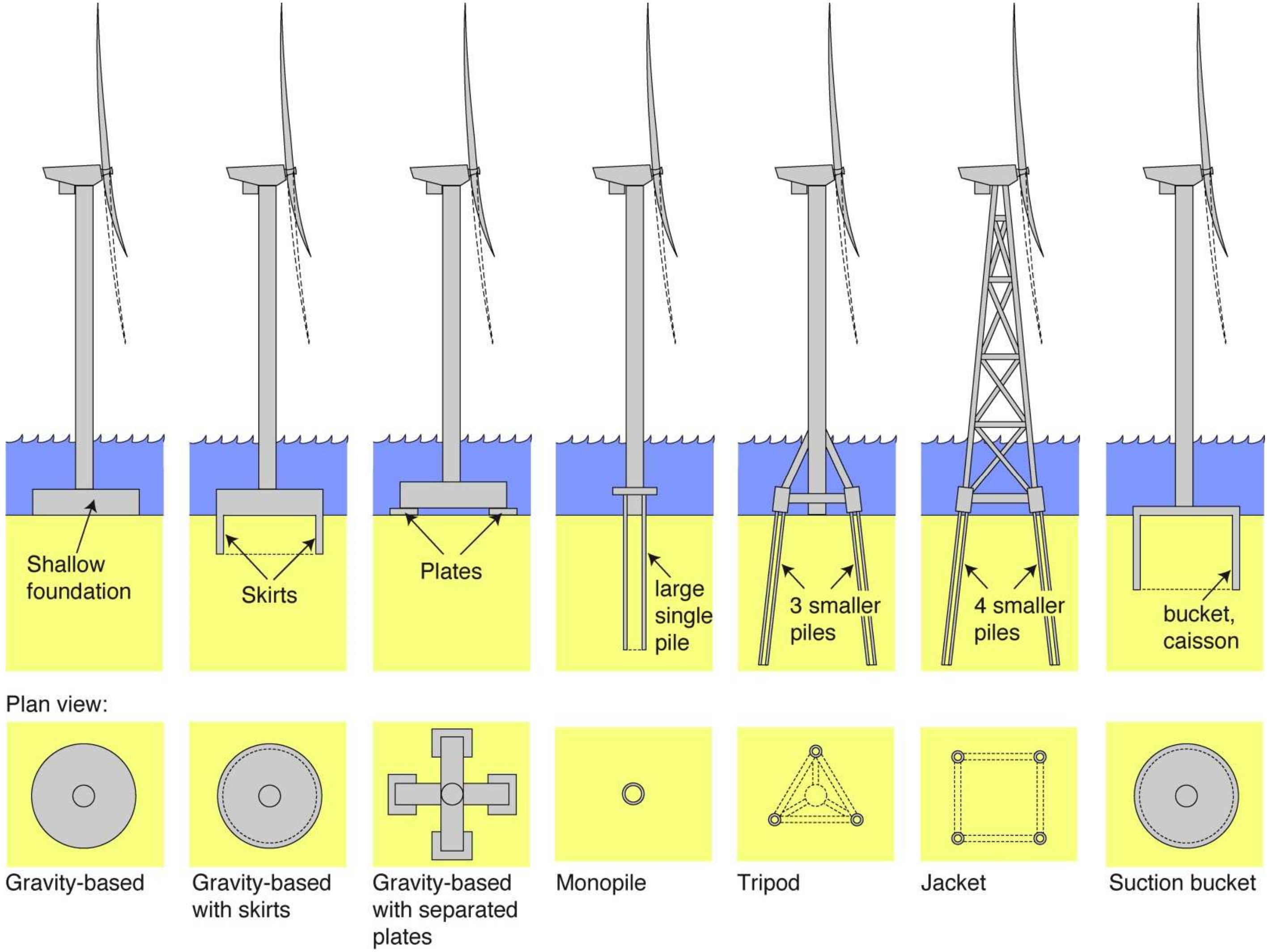
KIT-ZENTRUM ENERGIE

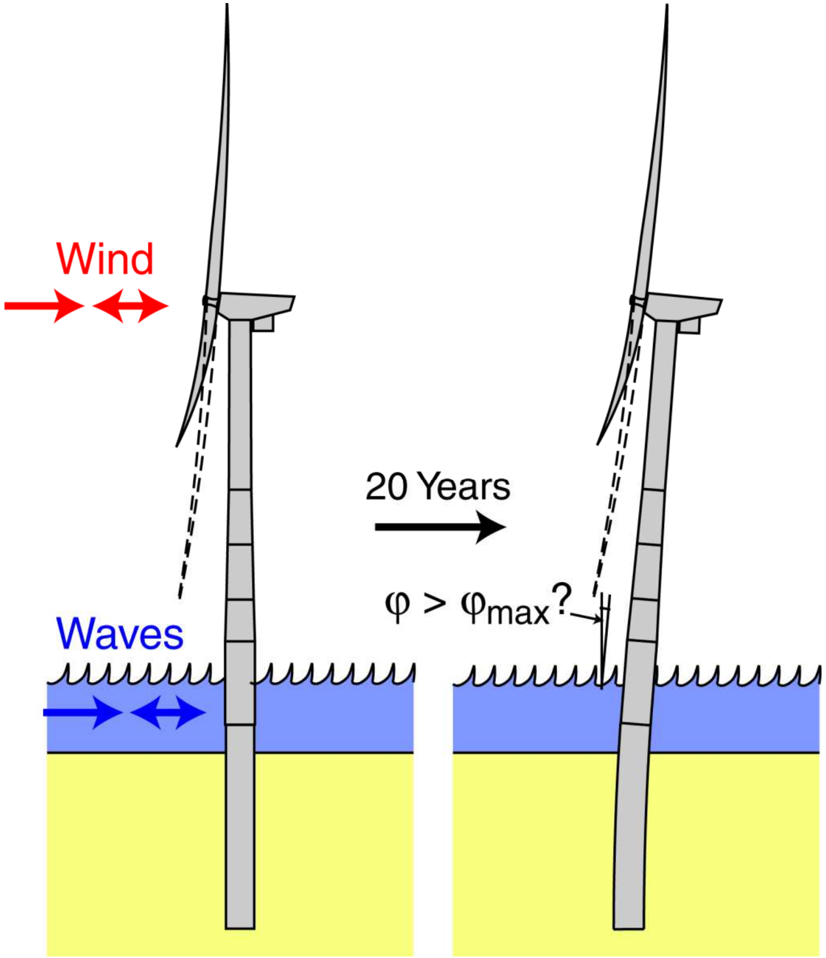
Foundation systems for offshore wind power generation



Here:

- Monopiles
- Shallow foundations

Loading on foundations

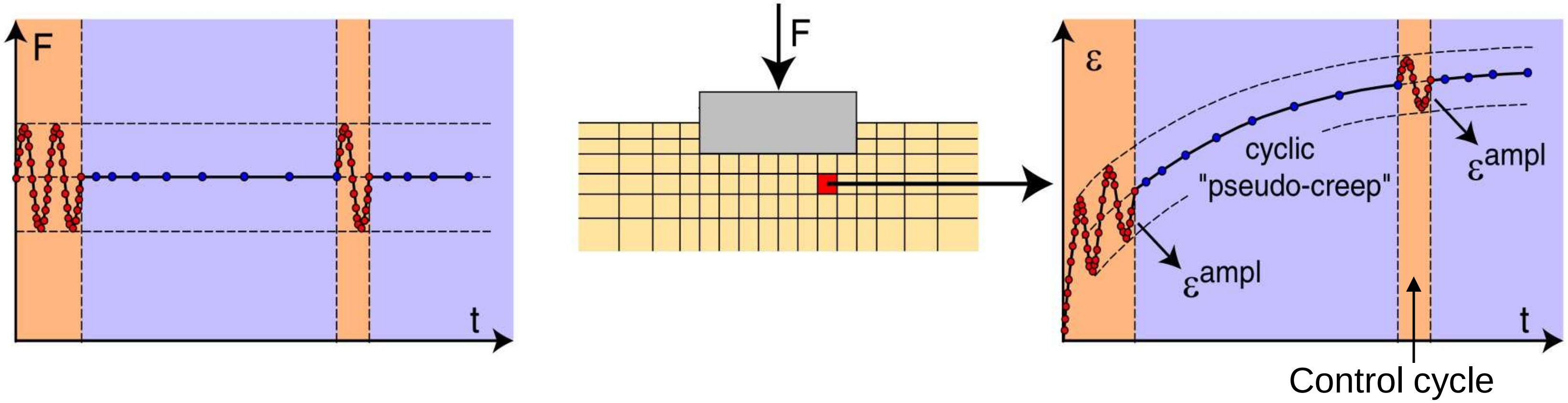


Problems:

- High number of loading cycles from wind and wave actions (stochastic, multidirectional)
- Serviceability of the structure (limited tilting and settlements)
- Erosion effects at the interface structure / soil (shallow foundations)
- Lack of experience on the long-term behavior of such structures

HCA – High Cycle Accumulation Model

Calculation strategy: coupled „implicit“ + „explicit“ calculation steps



- Only a few cycles are calculated incrementally using a $\dot{\sigma}$-$\dot{\varepsilon}$- model
- Larger packages of cycles ΔN in between are treated like creep deformations under constant load
- input of the accumulation model: strain amplitudes ε^{ampl} from implicit cycles
- advantages: 1) no limitations with respect to possible maximum cycle numbers

  2) much smaller number of increments → numerical errors minimized

HCA – High Cycle Accumulation Model

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

$\dot{\boldsymbol{\sigma}}$ Stress rate
E Elastic stiffness (pressure dependent)
$\dot{\boldsymbol{\varepsilon}}$ Strain rate
$\dot{\boldsymbol{\varepsilon}}^{\rm acc}$ Accumulation rate (given)
$\dot{\boldsymbol{\varepsilon}}^{\rm pl}$ Plastic strain rate (for strain paths touching the yield surface)

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

$\mathbf{m}$ Direction of strain accumulation (unit tensor)
→ Flow direction of MCC-Model
$\dot{\varepsilon}^{\rm acc}$ intensity of strain accumulation (scalar)

$$\dot{\varepsilon}^{\rm acc} = f_{\rm ampl}\,\dot{f}_N\,f_p\,f_Y\,f_e\,f_\pi$$

Amplitude definition for multidimensional loops

Functions (with material constants) consider:

$f_{\rm ampl}$ Strain amplitude (C_{ampl})
$\dot{f}_N$ Cyclic preload (C_{N1},C_{N2},C_{N3})
f_p, f_Y Average mean stress (C_p), stress ratio (C_Y)
f_e Void ratio (C_e)
f_π Polarization changes ($C_{\pi 1}$, $C_{\pi 2}$)

HCA – High Cycle Accumulation Model

Intensity of accumulation

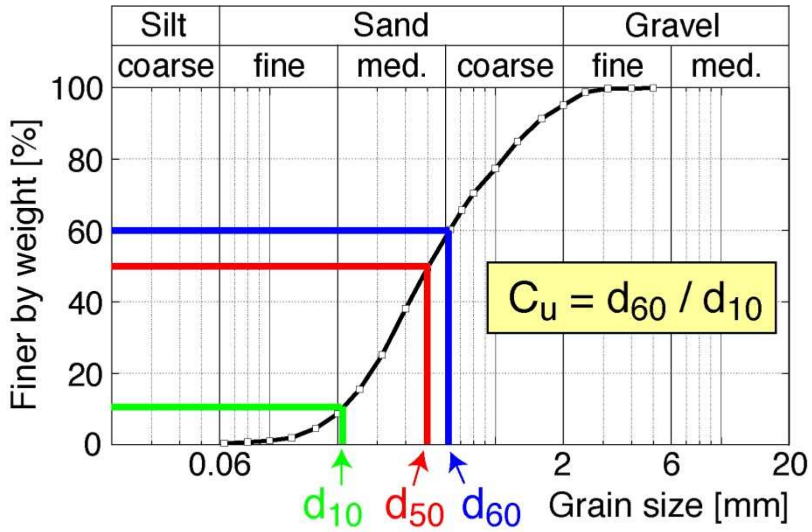
$$\dot{\varepsilon}^{\mathrm{acc}} = f_{\mathrm{ampl}}\ \dot{f}_N\ f_p\ f_Y\ f_e\ f_\pi$$

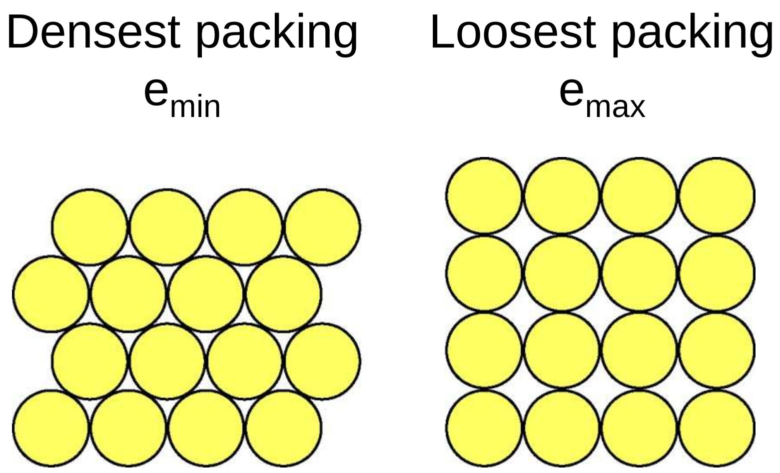
Influencing parameter	Function	Parameter
Strain amplitude $\varepsilon^{\mathrm{ampl}}$	$f_{\mathrm{ampl}} = \left(\frac{\varepsilon^{\mathrm{ampl}}}{10^{-4}}\right)^{C_{\mathrm{ampl}}}$	C_{ampl}
Void ratio e	$f_e = \frac{(C_e - e)^2}{1+e}\ \frac{1+e_{\max}}{(C_e - e_{\max})^2}$	C_e
Average mean pressure 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 (number of cycles)	$f_N = C_{N1}\ [\ln(1 + C_{N2}\ N) + C_{N3}\ N]$ $\dot{f}_N = C_{N1}\left[\frac{C_{N2}}{1+C_{N2}N} + C_{N3}\right]$	C_{N1} C_{N2} C_{N3}
Change of direction of cycles	f_π	$C_{\pi1}$, $C_{\pi2}$

Parameters of HCA model

Different ways to obtain a set of parameters (model calibration) :

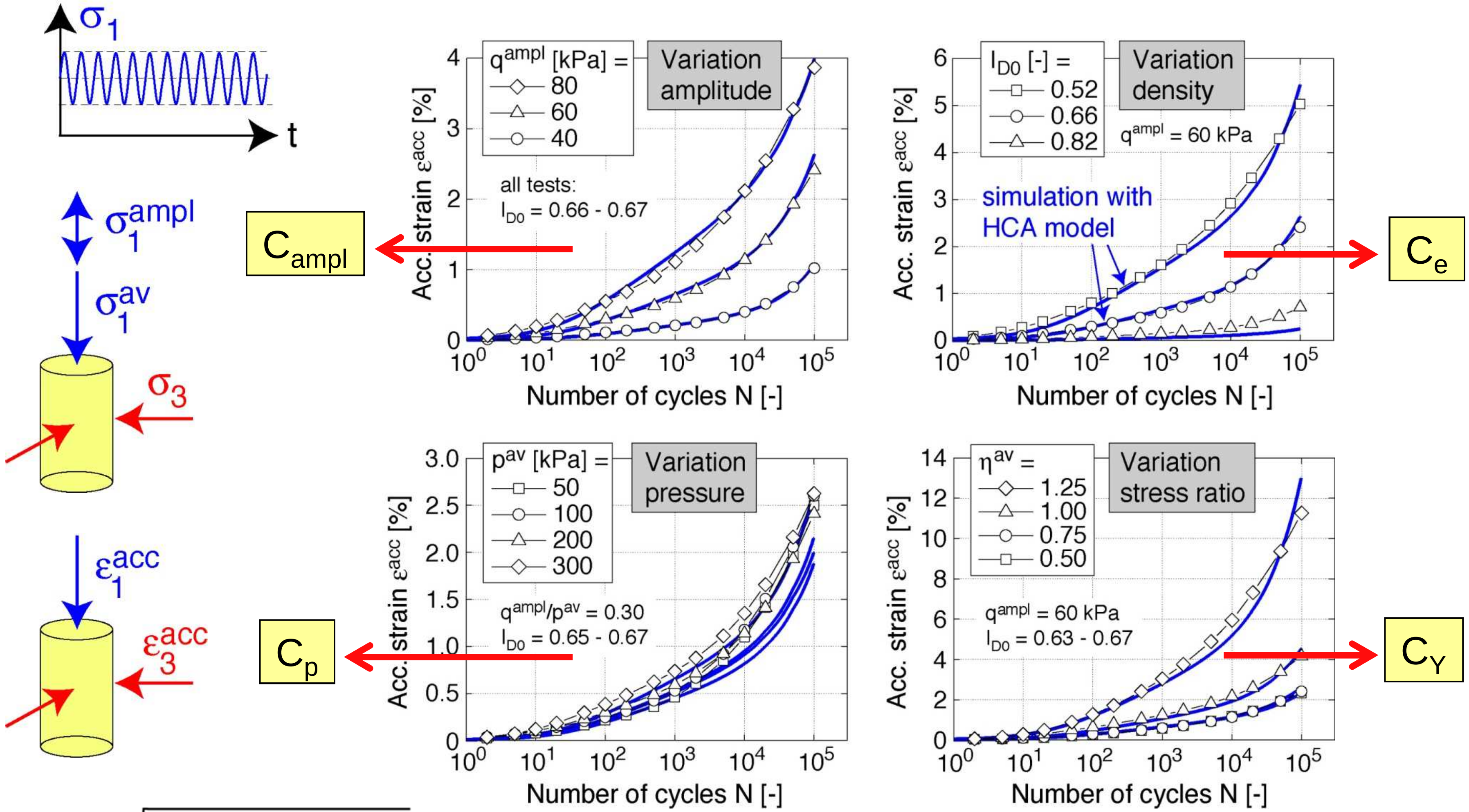
1. Determination of all parameters from at least 11 cyclic triaxial tests with different amplitudes, initial densities and average stresses
2. Estimation of C_{ampl}, C_p, C_e and C_Y from correlations with d_{50}, C_u and e_{min}, determination of C_{N1}, C_{N2} and C_{N3} from a single cyclic triaxial test
3. Estimation of all parameters from the correlations with d_{50}, C_u and e_{min}





Parameters of HCA model

From at least 11 cyclic triaxial tests



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

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

Parameters of HCA model

Simplified calibration based on the grain size distribution curve

Parameter	Correlation
C_{ampl}	$C_{\mathrm{ampl}} = 1.70$
C_e	$C_e = 0.95 \cdot e_{\min}$
C_p	$C_p = 0.41 \cdot [1 - 0.34\ (d_{50} - 0.6)]$
C_Y	$C_Y = 2.60 \cdot [1 + 0.12\ \ln(d_{50}/0.6)]$
C_{N1} C_{N2} C_{N3}	$C_{N1} = 4.5 \cdot 10^{-4} \cdot [1 - 0.306\ \ln(d_{50}/0.6)] \cdot [1 + 3.15\ (C_u - 1.5)]$ $C_{N2} = 0.31 \cdot \exp[0.39\ (d_{50} - 0.6)] \cdot \exp[12.3(\exp(-0.77\ C_u) - 0.315)]$ $C_{N3} = 3.0 \cdot 10^{-5} \cdot \exp[-0.84\ (d_{50} - 0.6)] \cdot [1 + 7.85\ (C_u - 1.5)]^{0.34}$

From about 350 cyclic triaxial tests on quartz sands with subangular grain shape and $0.1 \leq d_{50} \leq 6$ mm, $1.5 \leq C_u \leq 8$ (= range of validity)

Correlations will be extended by the influence of the grain characteristics (grain shape, surface roughness, mineralogy, etc.)

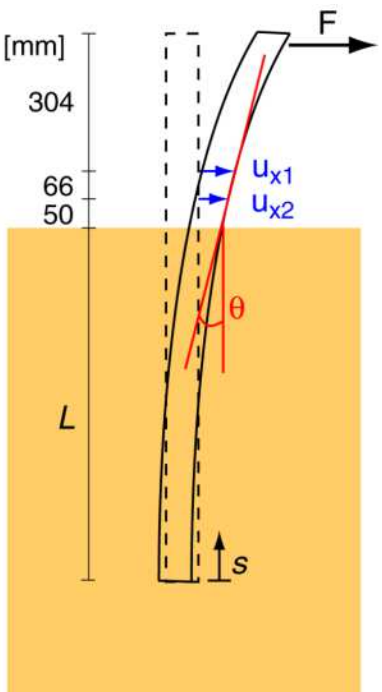
Validation of HCA model predictions

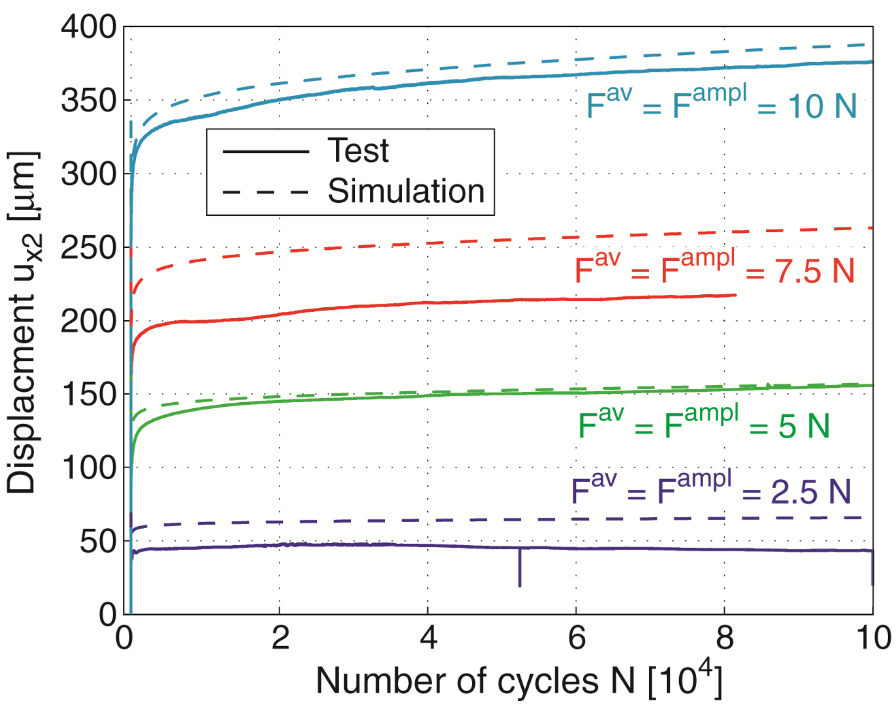
Based on small-scale model tests

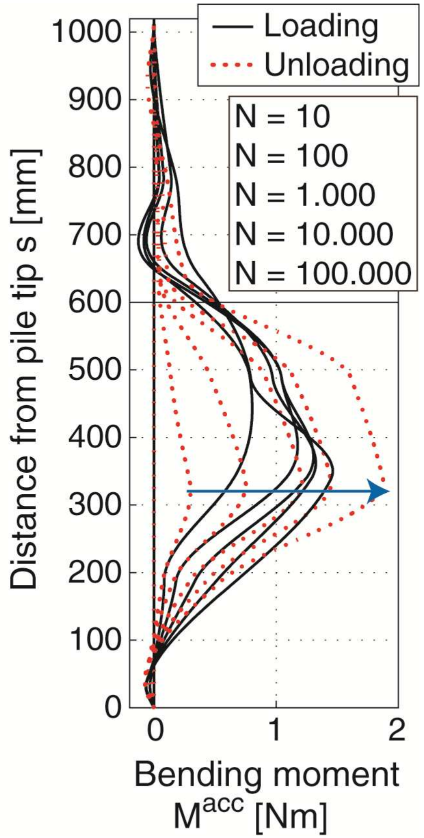
- Model tests on shallow and monopile foundations (1:50) with high-cyclic loading
- Aim: Inspection of the HCA model under clearly defined boundary conditions

Monopiles:

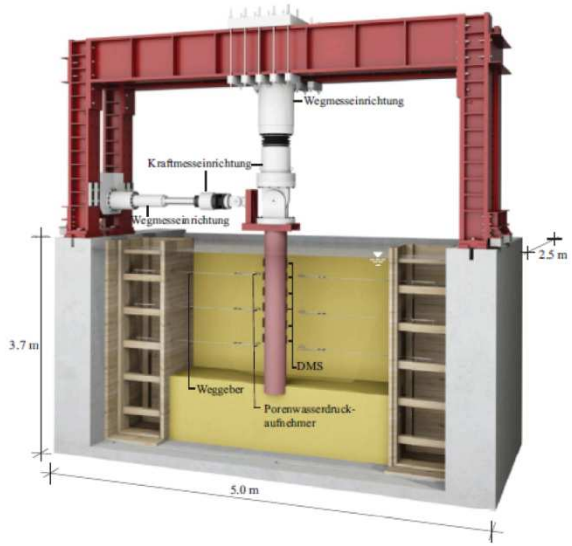
Bending moments in the pile due to accumulation effects under swelling loads





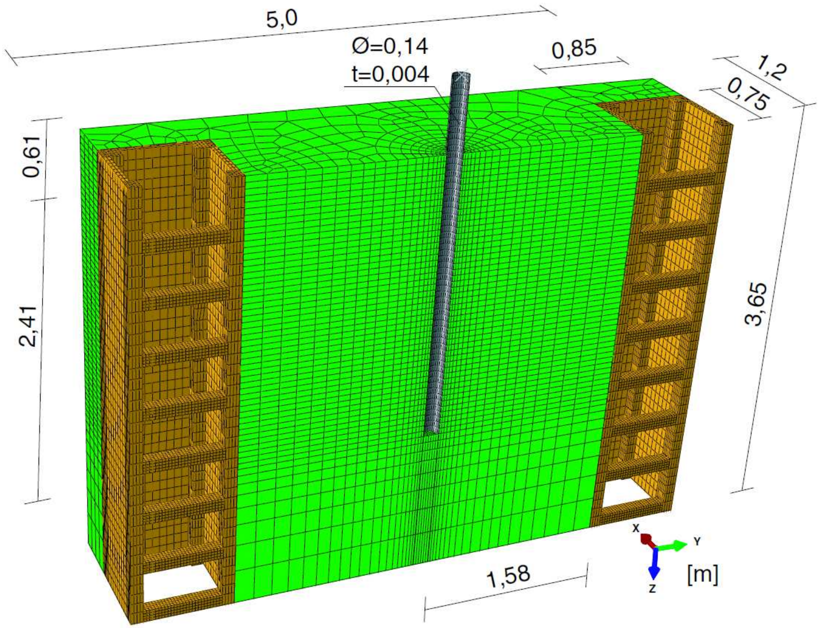


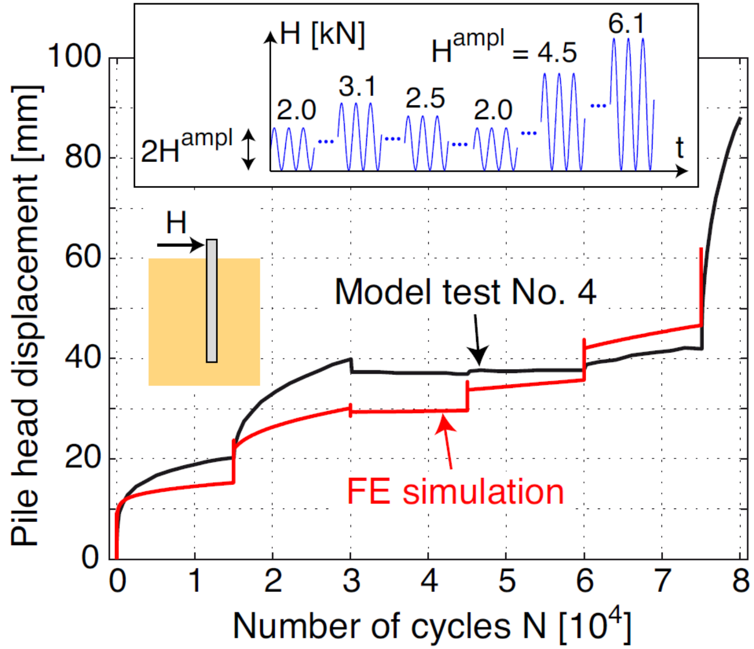
Validation of HCA model predictions



Based on large-scale model tests (1:10) at TU Berlin

- HCA model parameters of Berlin sand determined based on cyclic tests performed at IBF
- FE-Model:

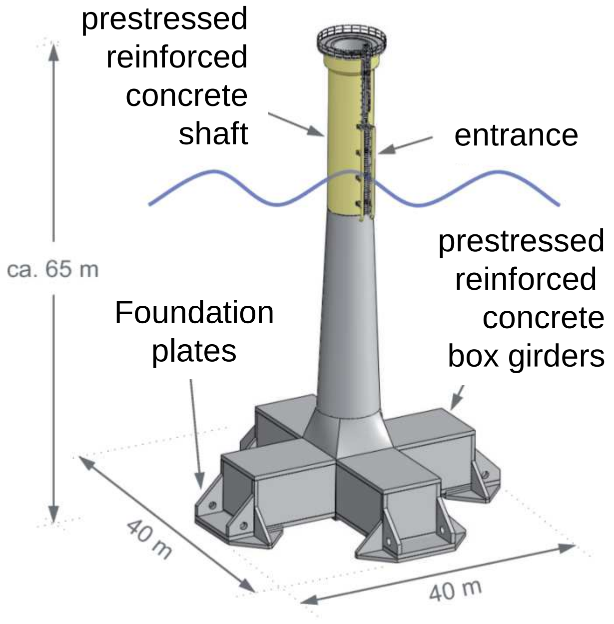




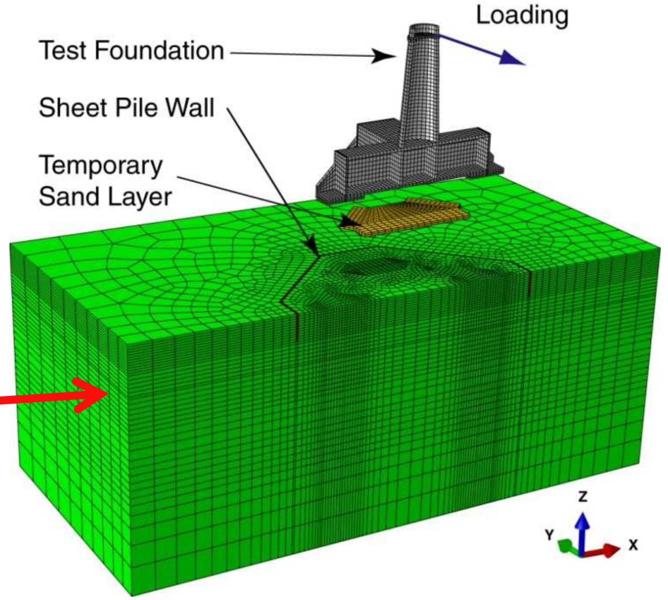
→ Good agreement between FE prediction and model test

Validation of HCA model predictions

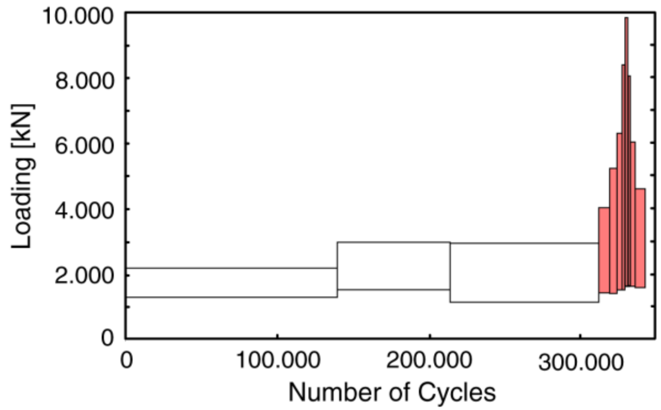
Based on full-scale test of Ed. Züblin AG
on a shallow foundation with high-cyclic loading
(1,5 Million cycles with different amplitudes)



- FE-model (87000 brick elements)
- Determination of HCA model parameters at IBF

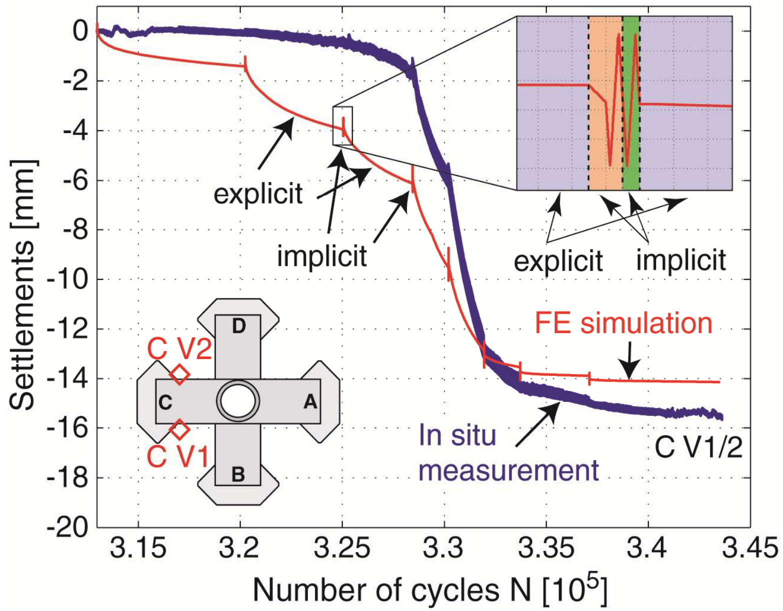


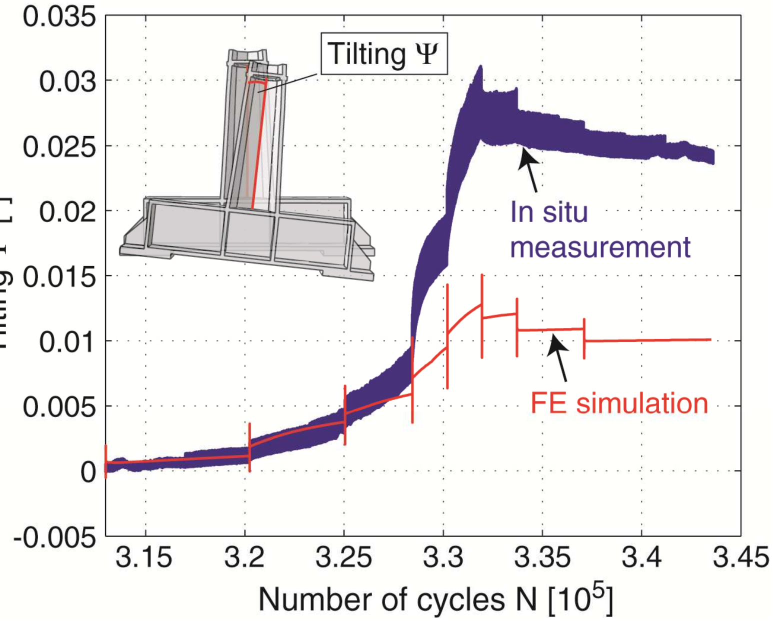
Validation of HCA model predictions



Based on full-scale test of Ed. Züblin AG
on a shallow foundation with high-cyclic loading

Comparison of measured and predicted accumulated settlements of foundation plate C and tilting of the foundation during the first storm event:

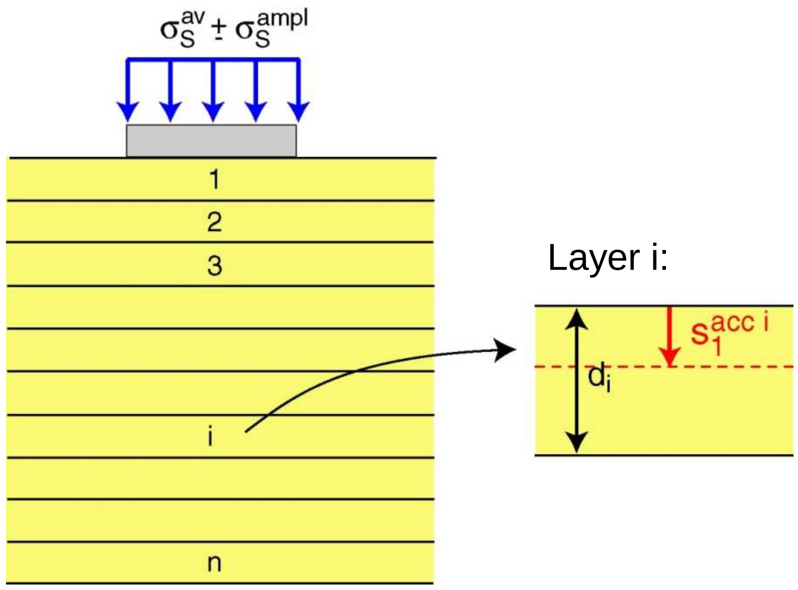




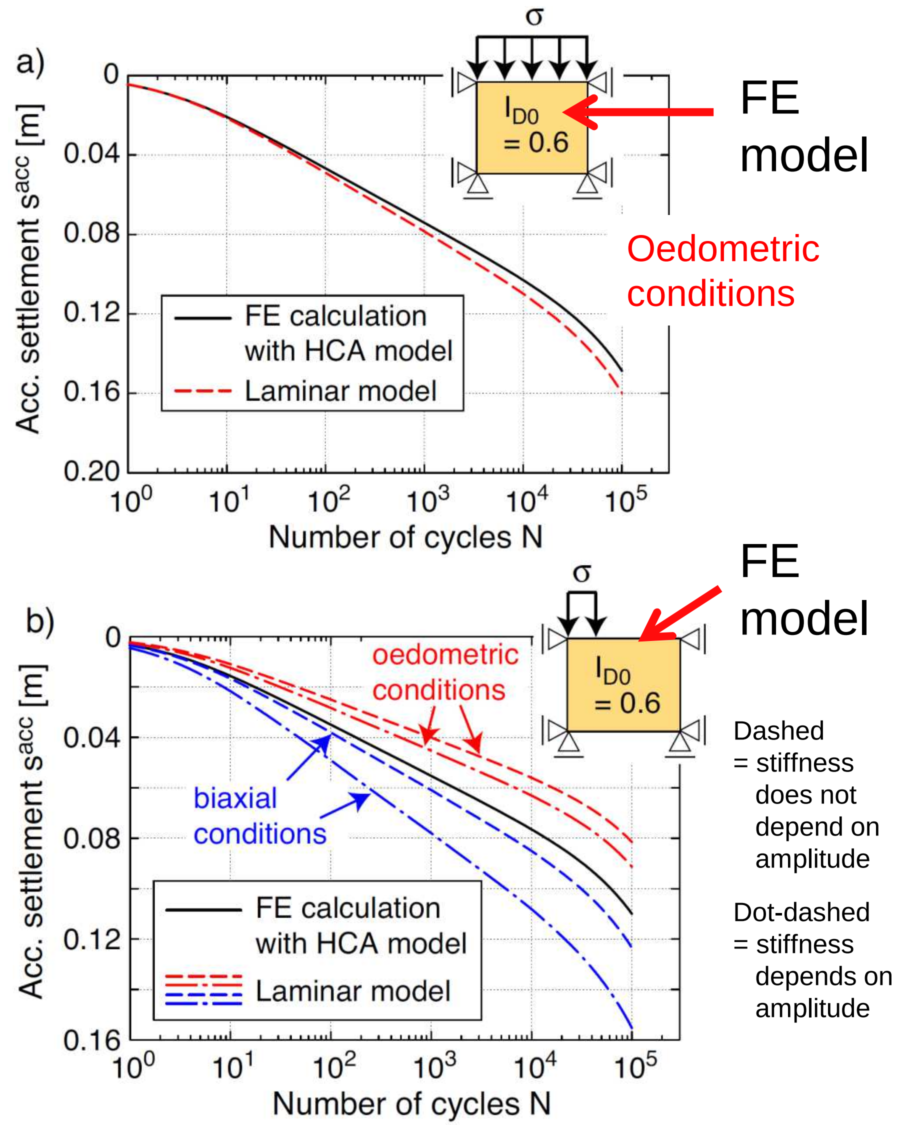
→ Good agreement between FE prediction and test regarding settlement, stress redistribution and pore water pressures

Simplified engineer-oriented models

Laminar model for a shallow foundation based on HCA model



→ Good agreement between FE and laminar model



Simplified engineer-oriented models

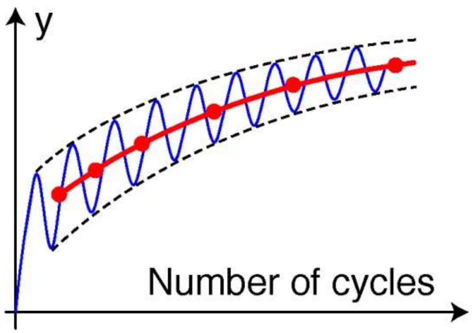
Laminar model for a monopile based on HCA model

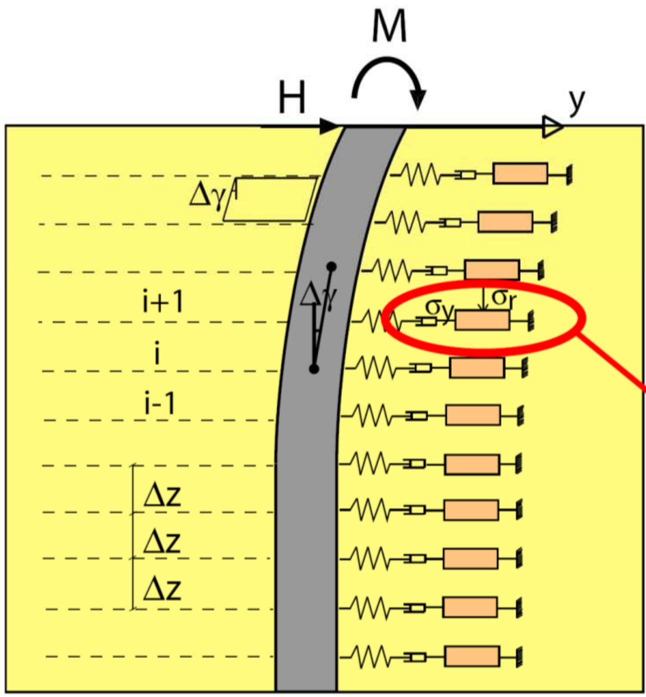
$$\epsilon_{ampl} = \Delta\gamma$$

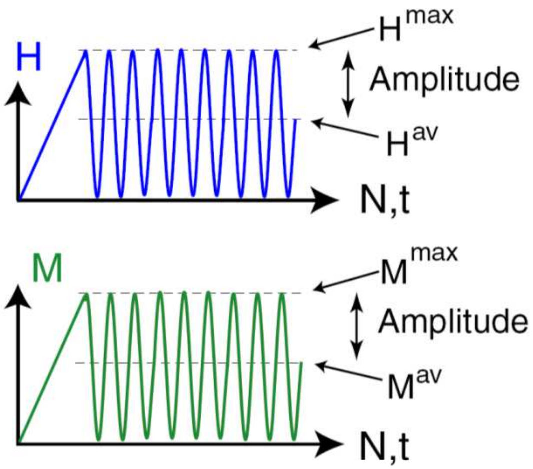
$$\dot{\epsilon}_v^{acc} = m_v \cdot \epsilon^{acc}$$

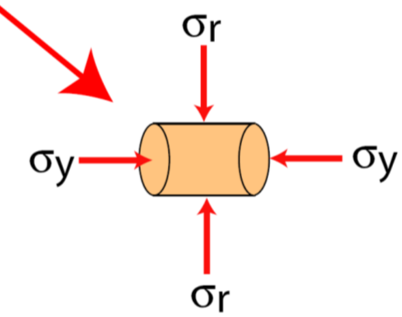
$$\dot{\epsilon}_q^{acc} = m_q \cdot \epsilon^{acc}$$

$$m_v,\ m_q:\ \text{flow rule}$$









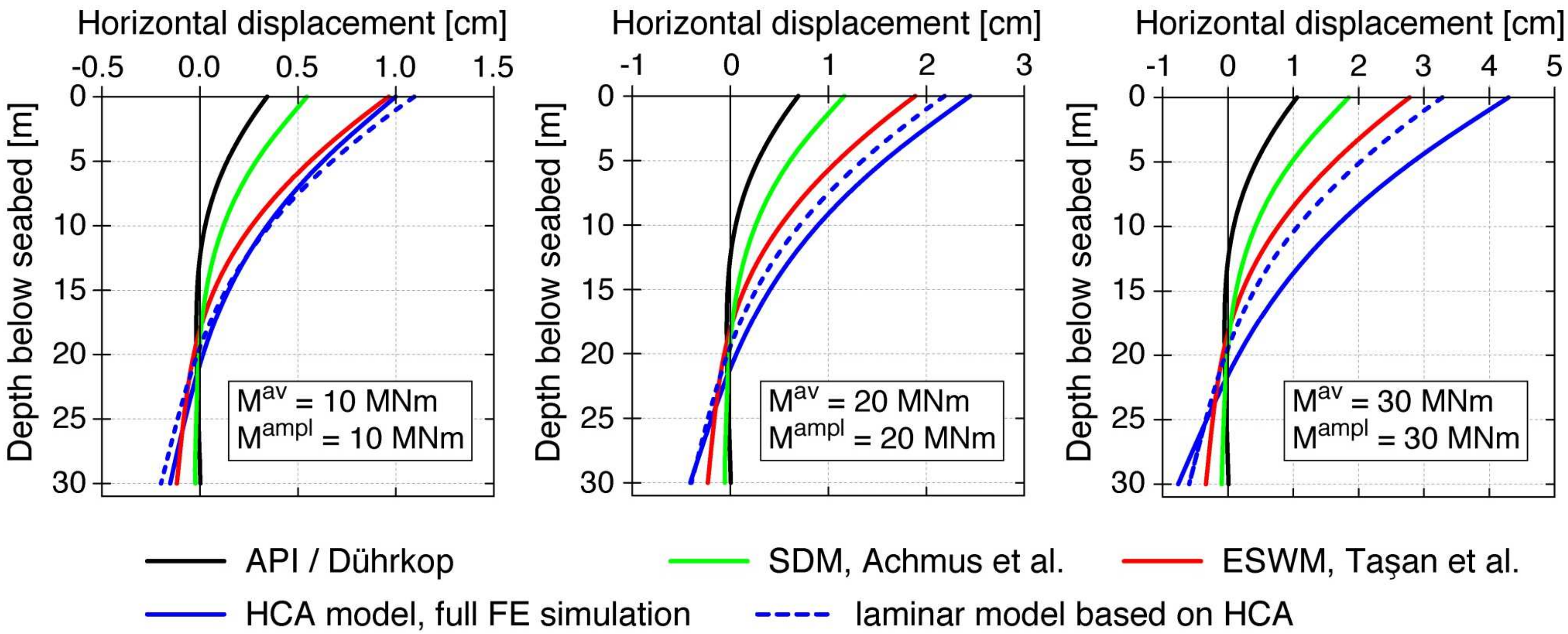
- Accumulation as pseudo-creep is represented by the dashpot
- Spring represents elastic stiffness of layer

Simplified engineer-oriented models

Laminar model for a monopile based on HCA model

Comparison of different models (here: I_{D0} = 0.6, M/Q = 20 m)

After monotonic loading to M^{max}:

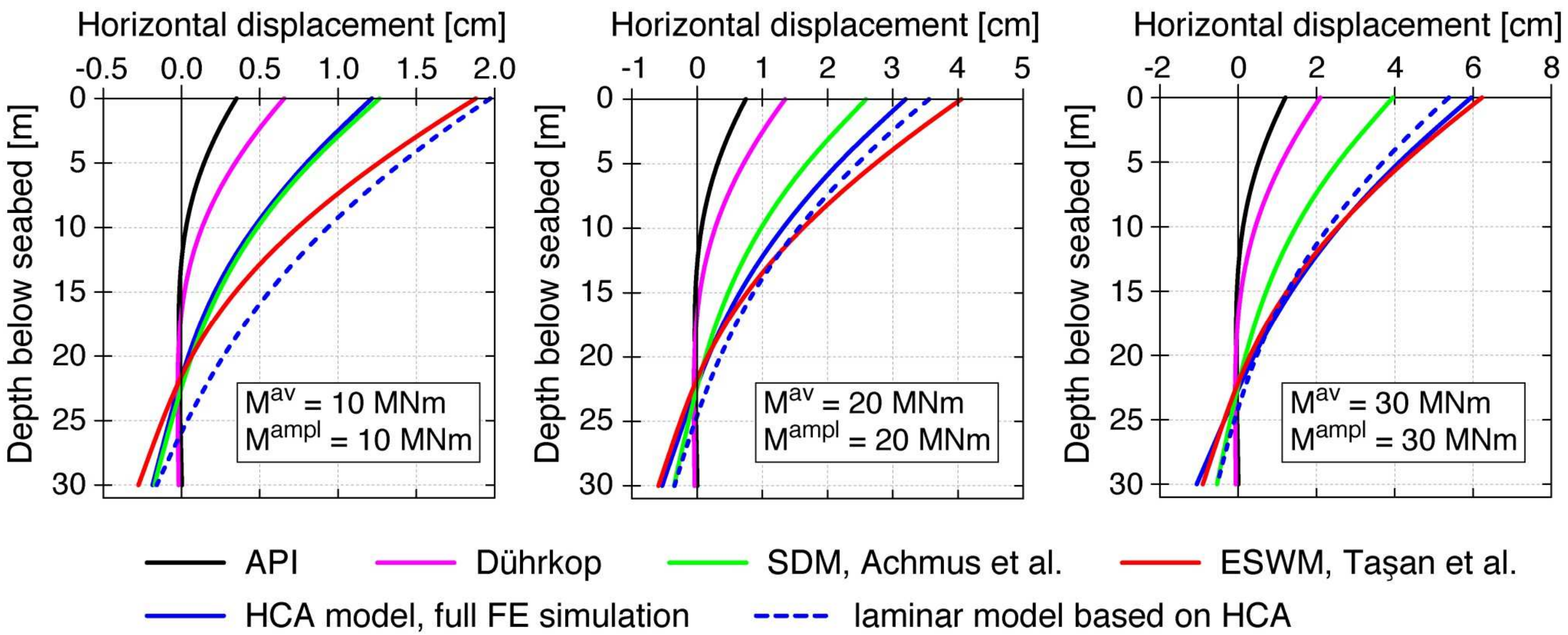


Simplified engineer-oriented models

Laminar model for a monopile based on HCA model

Comparison of different models (here: I_{D0} = 0.6, M/Q = 20 m)

After 100000 cycles:



Conclusions

HCA model requires:

- Cyclic triaxial tests
- Detailed determination of material parameters and soil parameters

HCA model provides:

- Very good agreement with small scale model tests on monopiles and shallow foundations (not shown here)
- Good agreement with the test foundation in real scale (settlements, PWP-development and contact pressure rearrangement)

$\Rightarrow$ HCA model is regarded to be validated (from model to real scale)

Advantages of HCA model against other simplified models:

- Captures the whole soil structure interaction
- Ability to investigate in detail the effects of accumulation or back rotation
- Flexible in application to conventional or new types of foundation structure or to any boundary value problem without restrictions

Thank you for your attention