Cyclic Loading of soils and simulation of accumulation phenomena- Applications to offshore wind turbines

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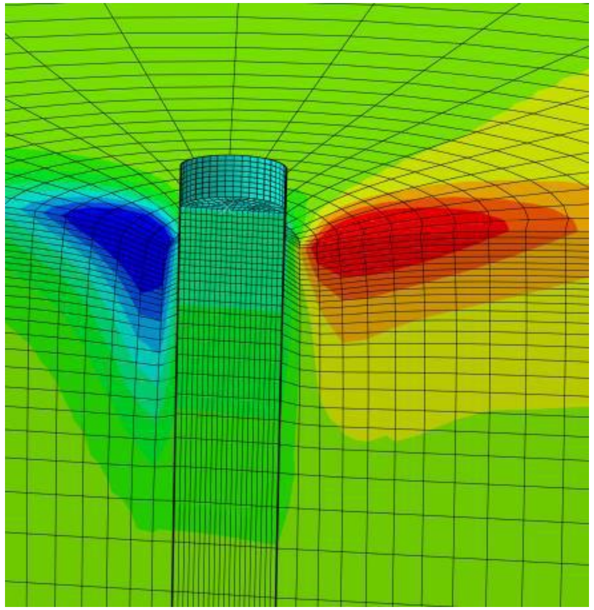

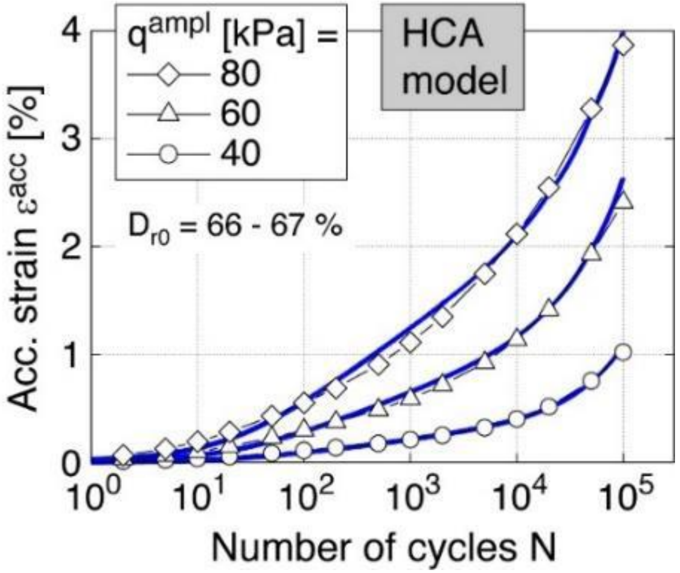

DAAD Deutscher Akademischer Austausch Dienst German Academic Exchange Service
KIT Karlsruhe Institute of Technology
UNIVERSITY OF PATRAS

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- High Cycle Loading on wind turbine structures
- High cycle accumulation model (HCA)
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- Validation of the HCA Model with physical modeling and in situ testing
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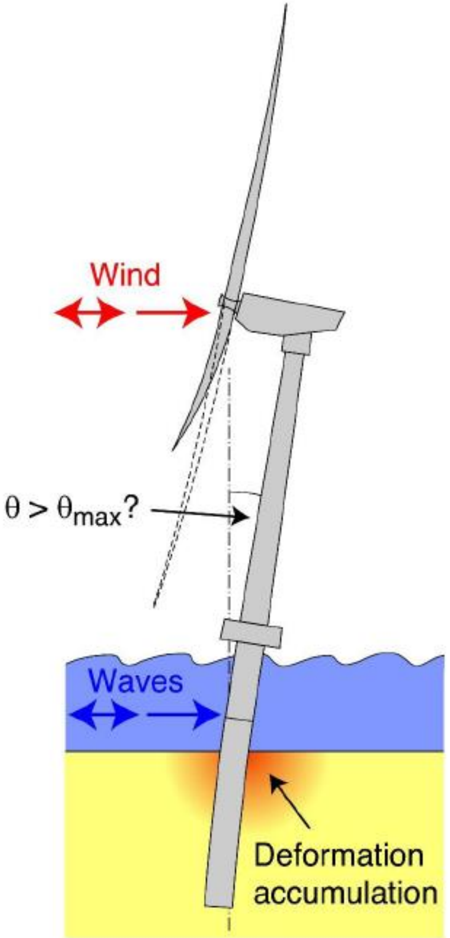
- Summary

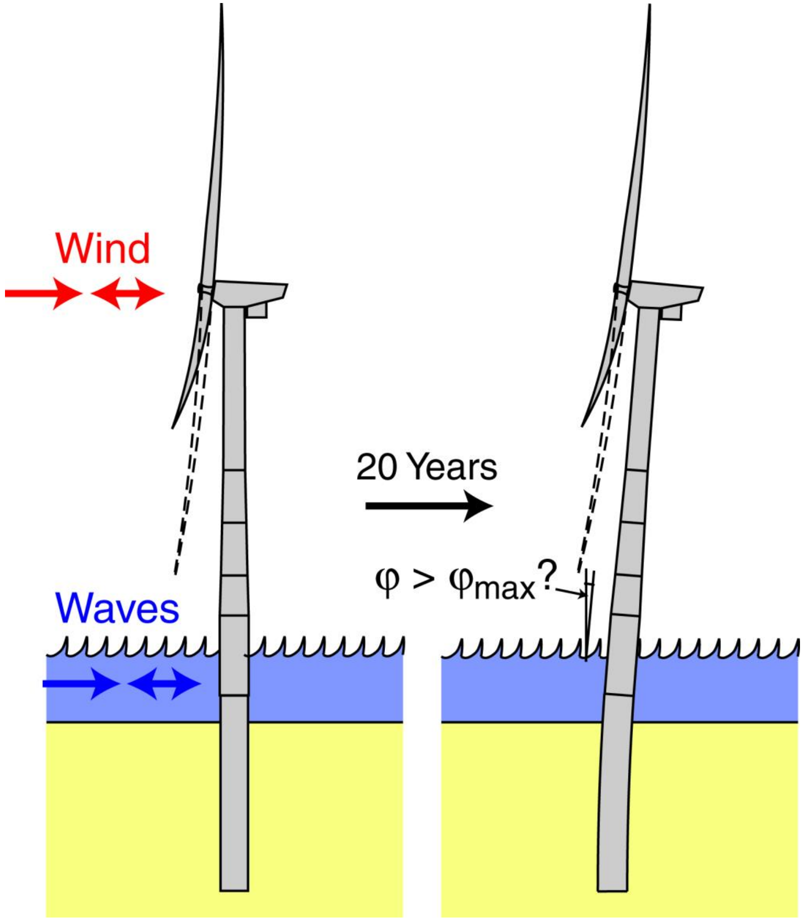
Why High cycle Loading in WT Design?

- WT structure has to resist a significant number of loading cycles and react with small deformations per loading cycle (accumulation)
- Typically small values of deformation amplitudes ($\varepsilon \leq 10^{-3}$) but large number of cycles N ($N \geq 10^{6}$) in their lifetime



Serviceability of WT in its lifetime is of high importance like the tilding angle of the tower at the position of the turbine bearings as well as the deformations of the soil surrounding the monopile foundation as supporting structural element

HCA Problems for WT foundations



Problems:

- High number of loading cycles from wind and wave actions (stochastic, multidirectional, changing amplitude and direction)

  Serviceability of the structure (limited tilting and settlements)

  Erosion effects at the interface structure / soil (shallow foundations)

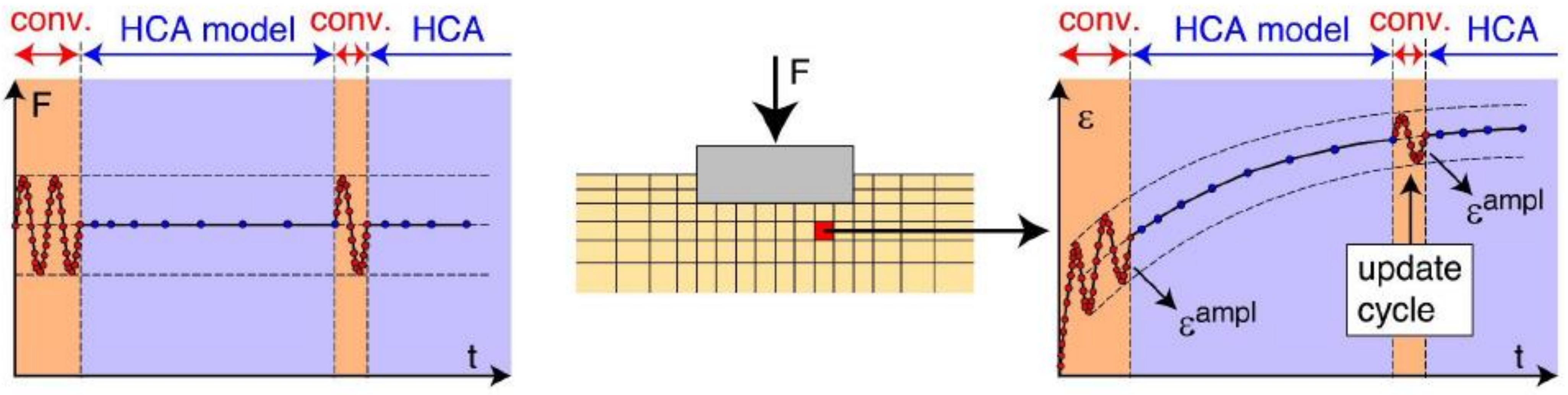
  Lack of experience on the long-term behavior of such structures

Numerical Strategies

- Implicit Formulation of accumulation using incremental formulations:
- $\partial\sigma/\partial t = E\,(\partial\varepsilon/\partial t - \partial\varepsilon^{acc}/\partial t)$ for every time step (10^4-10^6 No. of cycles)
- Problem: The numerical error is in the same order as the expected result of the boundary value problem
- Explicit Formulation of the accumulation for a bundle of cycles
- $\varepsilon^{acc,\,\Delta N} = f(\varepsilon^{ampl}, \sigma, e, \Delta N, \ldots)$ i.e. the accumulation for a great number of cycles ΔN can be expressed as the plastic deformation of a dashpot $\partial\varepsilon^{acc}/\partial N = C$, where the time is expressed as the number of cycles N (like creep deformations)

HCA – High Cycle Accumulation Model

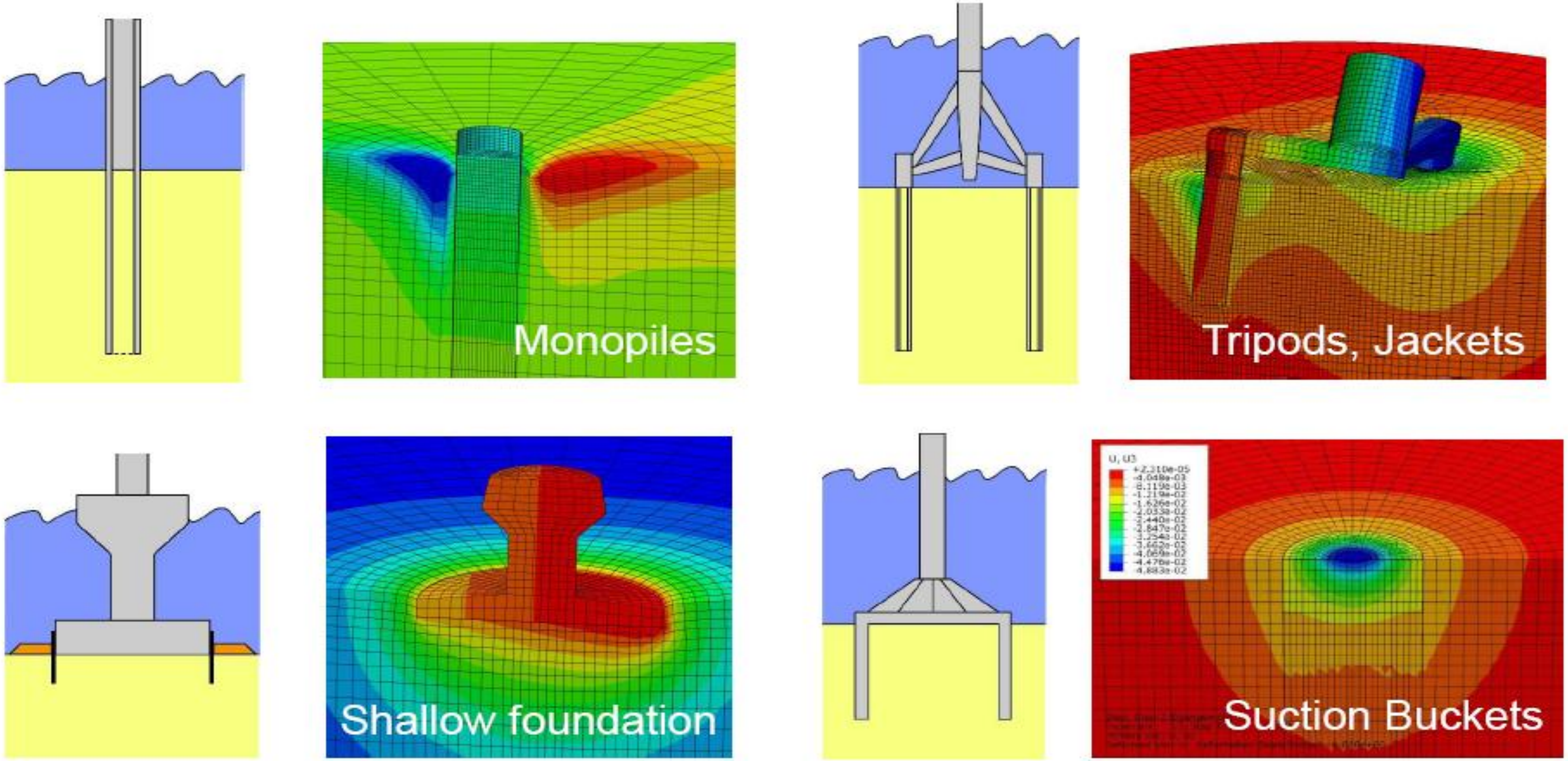
Calculation strategy: coupled „implicit“ + „explicit“ calculation steps



- Only a few cycles are calculated incrementally using an implicit model $\dot{\sigma}$-$\dot{\varepsilon}$-
- Larger packages of cycles ΔN in between are treated like creep deformations under constant load
- input of the accumulation model: strain amplitudes ε^{ampl} (determined from the cycles calculated conventionaly), void ratio, average stress, deviator stress…..
- advantages: 1) no limitations with respect to possible maximum cycle numbers
  2) much smaller number of increments → numerical errors minimized (conventional models usually restricted to N < 100)

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



HCA – High Cycle Accumulation Model

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

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

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

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

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

Amplitude definition for multidimensional loops

Functions (with material constants) consider:

f_{ampl} Strain amplitude (C_{ampl})
$\dot{f}_N$ Cyclic preloading (C_{N1},C_{N2},C_{N3})
f_p, f_Y Average mean stress (C_p), average stress ratio (C_Y), $\eta^{av}=q^{av}/p^{av}$
f_e Void ratio (C_e)
f_π Changes of the direction of cycles ($C_{\pi 1}$, $C_{\pi 2}$), may neglected i.e. $f_\pi = 1$

Niemunis, A., Wichtmann, T., Triantafyllidis, Th. (2005): A high-cycle accumulation model for sand. Computers and Geotechnics, Vol. 32, No. 4, pp. 245-263.

HCA – High Cycle Accumulation Model

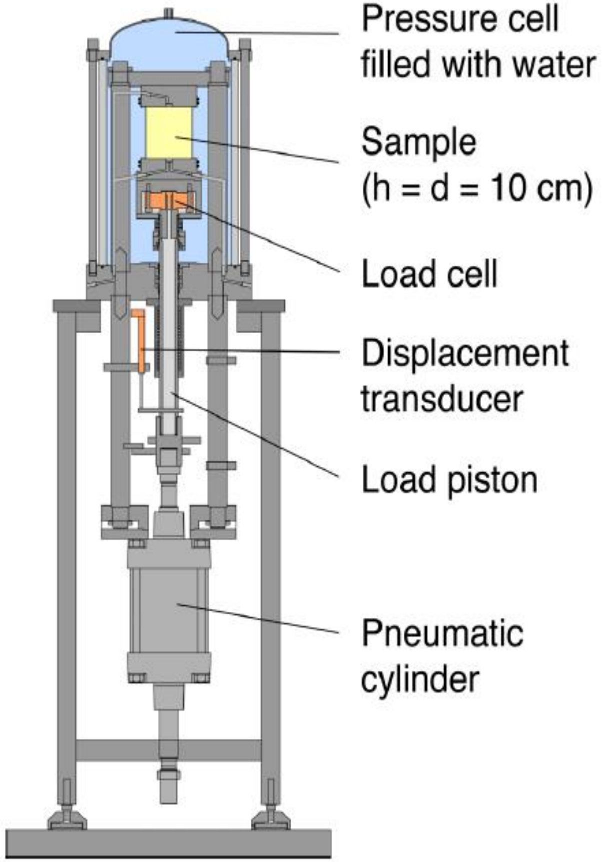
Intensity of accumulation

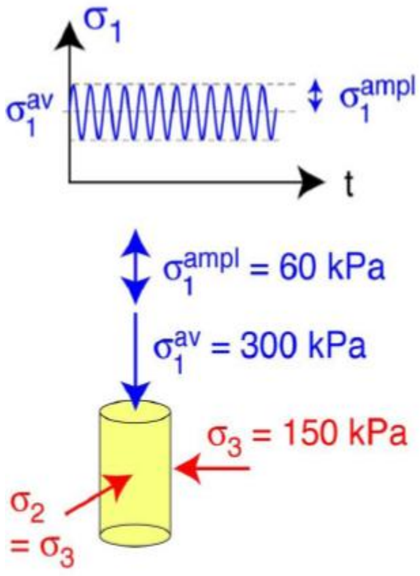
$$\dot{\varepsilon}^{acc} = f_{ampl}\ \dot{f}_N\ f_p\ f_Y\ f_e\ f_\pi$$

Influencing parameter	Function	Parameter
Strain amplitude ε^{ampl}	$f_{ampl} = \left(\frac{\varepsilon^{ampl}}{10^{-4}}\right)^{C_{ampl}}$	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}	$f_p = \exp\left[-C_p\ \left(\frac{p^{av}}{100\ \text{kPa}} - 1\right)\right]$	C_p
Average stress ratio Y^{av}	$f_Y = \exp(C_Y\ \bar{Y}^{av})$	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	$C_{\pi1}$, $C_{\pi2}$

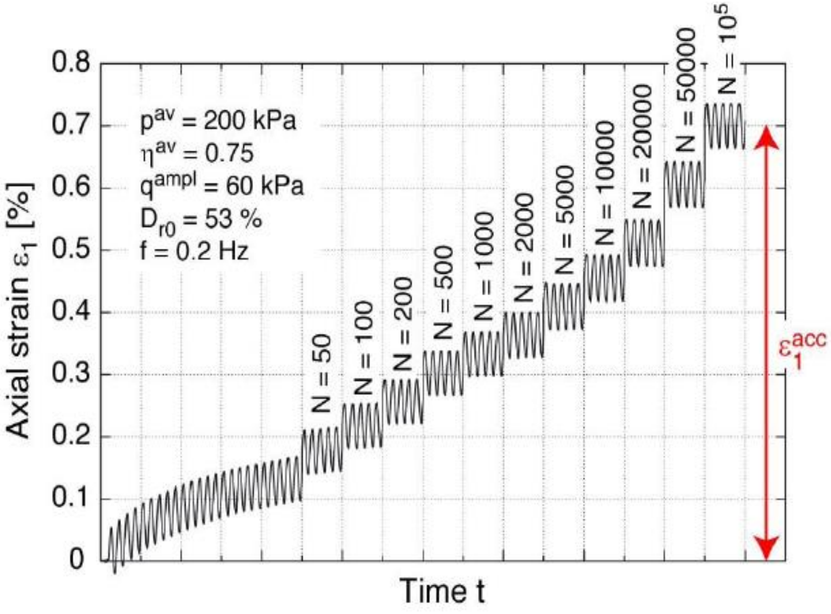
Calibration of the HCA Model based on drained cyclic triaxial tests

KIT, Karlsruhe





σ = effective stress



Wichtmann, T., Niemunis, A., Triantafyllidis, Th. (2005): Strain accumulation in sand due to cyclic loading: drained triaxial tests. Soil Dynamics and Earthquake Engineering, Vol. 25, No. 12, pp. 967-979.

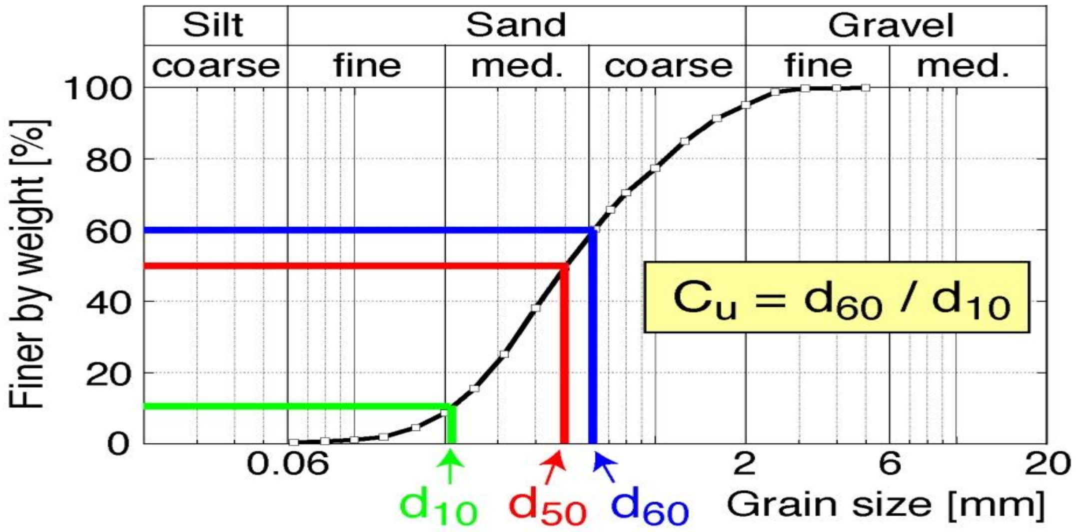
Typical result of a drained cyclic triaxial test on an medium dense soil sample (relative density D_{r0} = 0,53) of fine sand

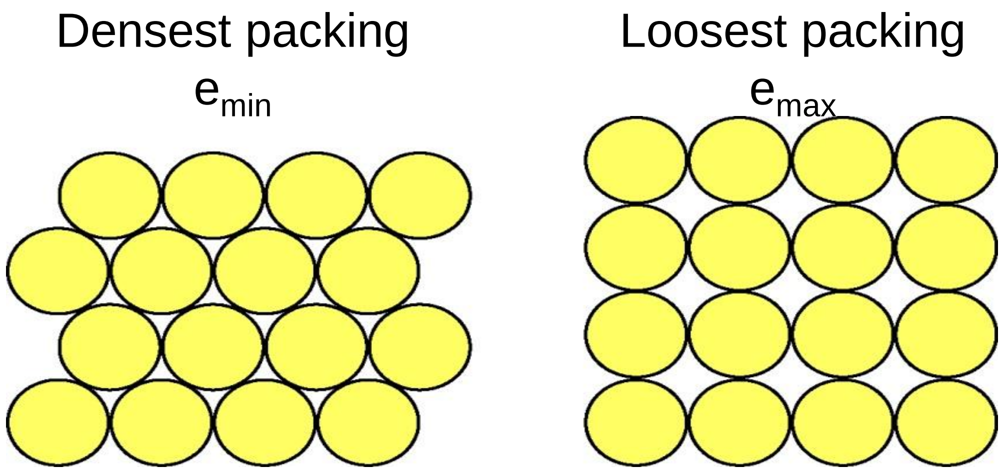
At the University of Patras the same device available

Parameters of HCA model

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

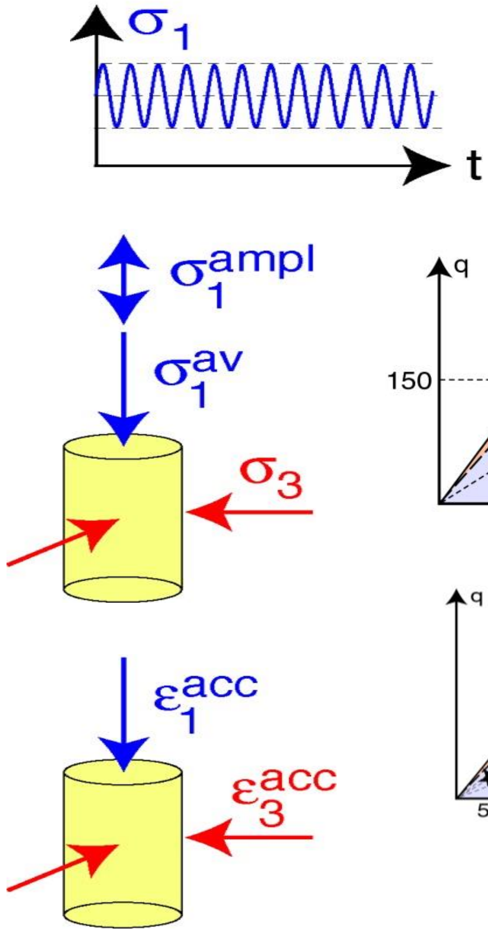
1. Determination of all parameters from at least 11 cyclic triaxial tests with different amplitudes, initial densities and average stresses
2. Estimation of C_{ampl}, C_p, C_e and C_Y from correlations with d_{50}, C_u and e_{min}, determination of C_{N1}, C_{N2} and C_{N3} from a single cyclic triaxial test (large number of cycles 10^5)
3. Estimation of all parameters from the correlations with d_{50}, C_u and e_{min}



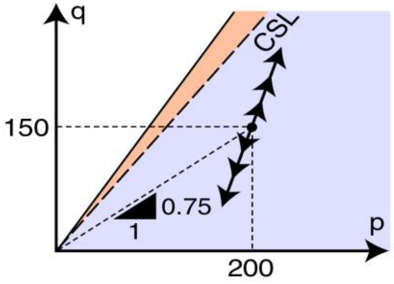


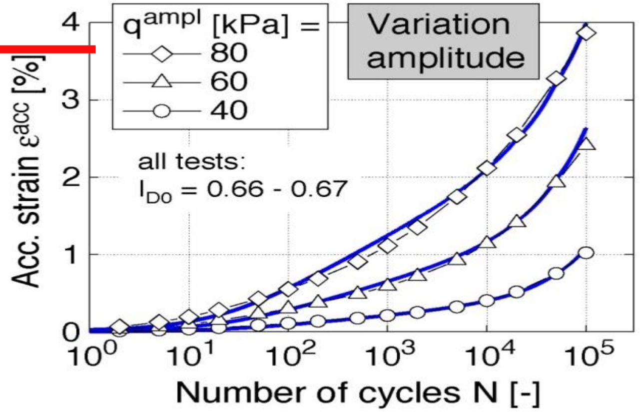
Parameters of HCA model

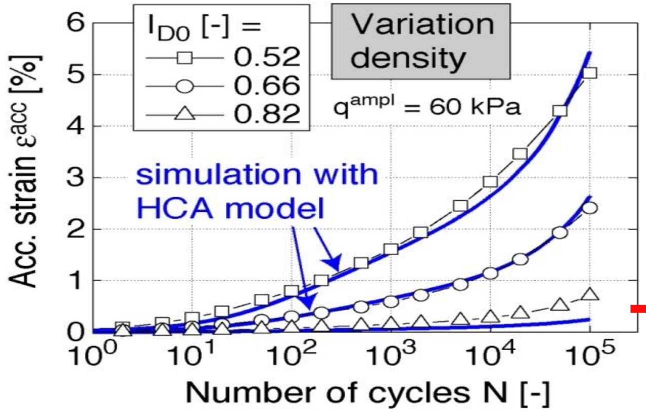
From at least 11 cyclic triaxial tests

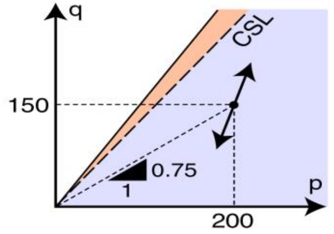


C_{ampl}

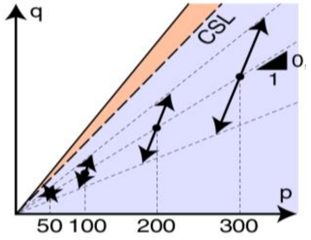


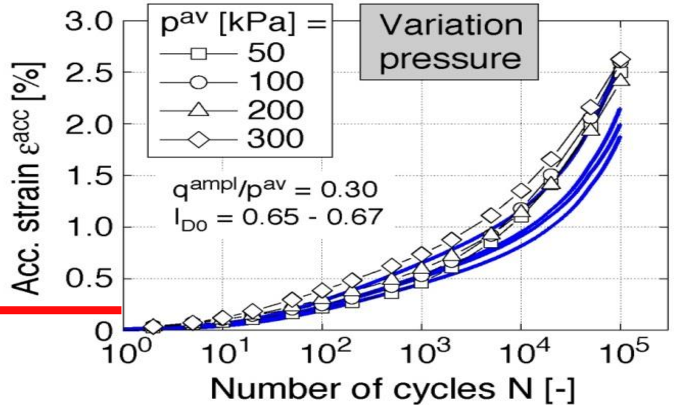


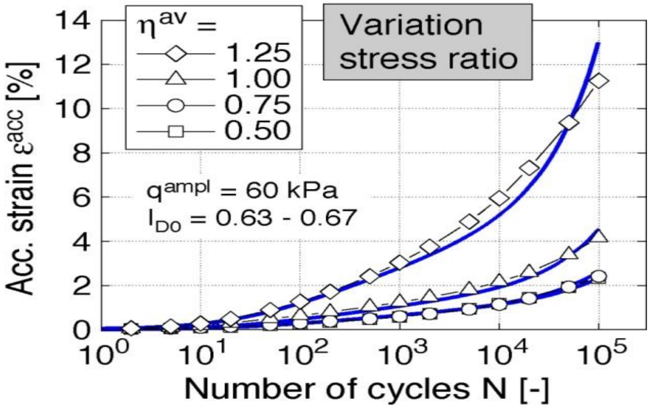




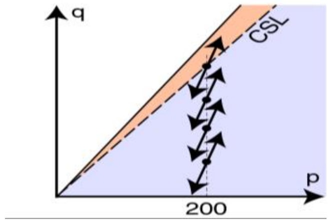
C_e







C_Y



C_p

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

From all tests: C_{N1}, C_{N2}, C_{N3} via curve fitting $\varepsilon^{acc}/(f_{ampl}\ f_p\ f_e\ f_Y)$ versus N

Parameters of HCA model

Simplified calibration based on the grain size distribution curve

Para-meter	Correlation
C_{ampl}	$C_{\text{ampl}} = 1.70$
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}	$C_{N1} = 4.5 \cdot 10^{-4} \cdot [1 - 0.306\ \ln(d_{50}/0.6)] \cdot [1 + 3.15\ (C_u - 1.5)]$ $C_{N2} = 0.31 \cdot \exp[0.39\ (d_{50} - 0.6)] \cdot \exp[12.3(\exp(-0.77\ C_u) - 0.315)]$ $C_{N3} = 3.0 \cdot 10^{-5} \cdot \exp[-0.84\ (d_{50} - 0.6)] \cdot [1 + 7.85\ (C_u - 1.5)]^{0.34}$

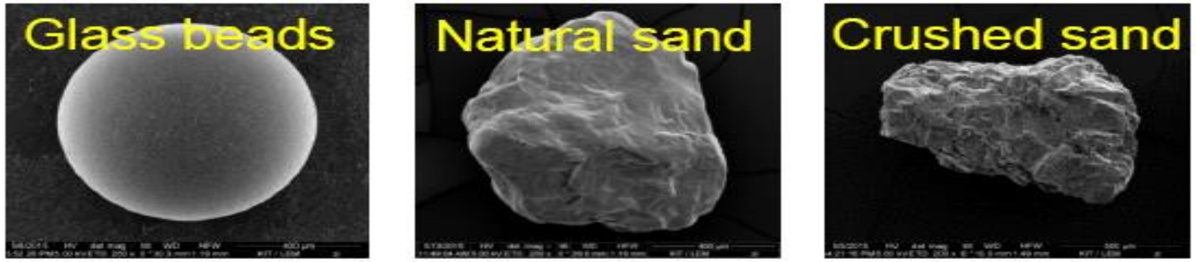
From about 350 cyclic triaxial tests on quartz sands with subangular grain shape and $0.1 \leq d_{50} \leq 6$ mm, $1.5 \leq C_u \leq 8$ (= range of validity)

Wichtmann, T., Niemunis, A., Triantafyllidis, Th. (2015): Improved simplified calibration procedure for a high-cycle accumulation model. Soil Dynamics and Earthquake Engineering, Vol. 70, pp. 118-132.

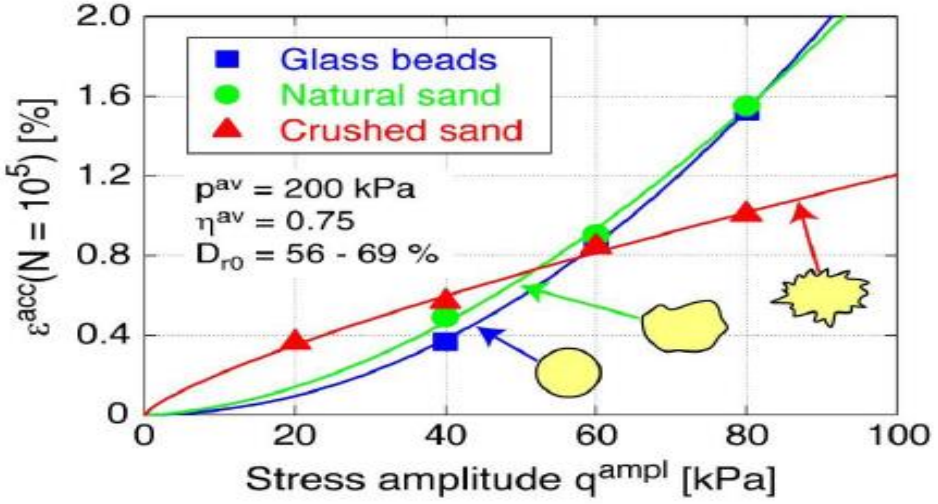
Influence of grain characteristics shape, roughness, mineralogy etc.

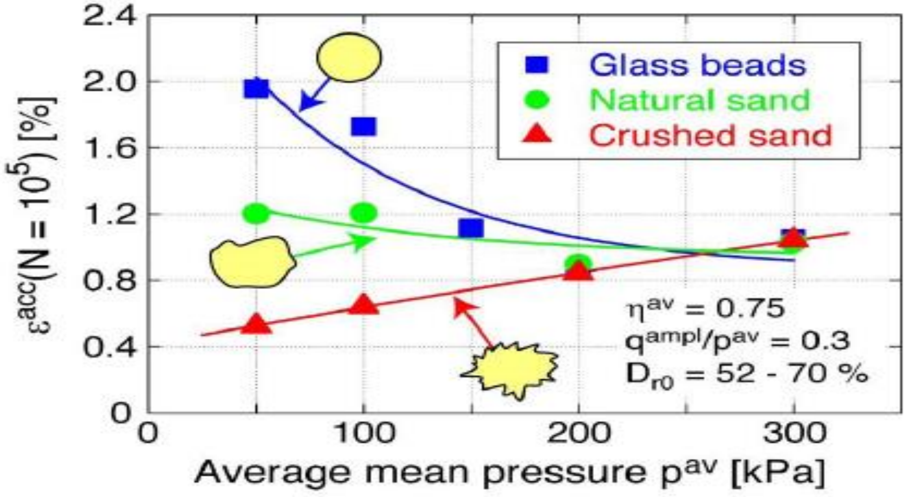
Particle shape – surface roughness

Wichtmann, T., Triantafyllidis, Th., Späth, L. (2019): On the influence of grain shape on the cumulative deformations in sand under drained high-cyclic loading. Soils and Foundations. Vol. 59, No. 1, pp. 208-227.



Three materials possess different grain shape and surface roughness but identical grain size distribution curve (d_{50} = 0.6 mm, C_u = 1.5)



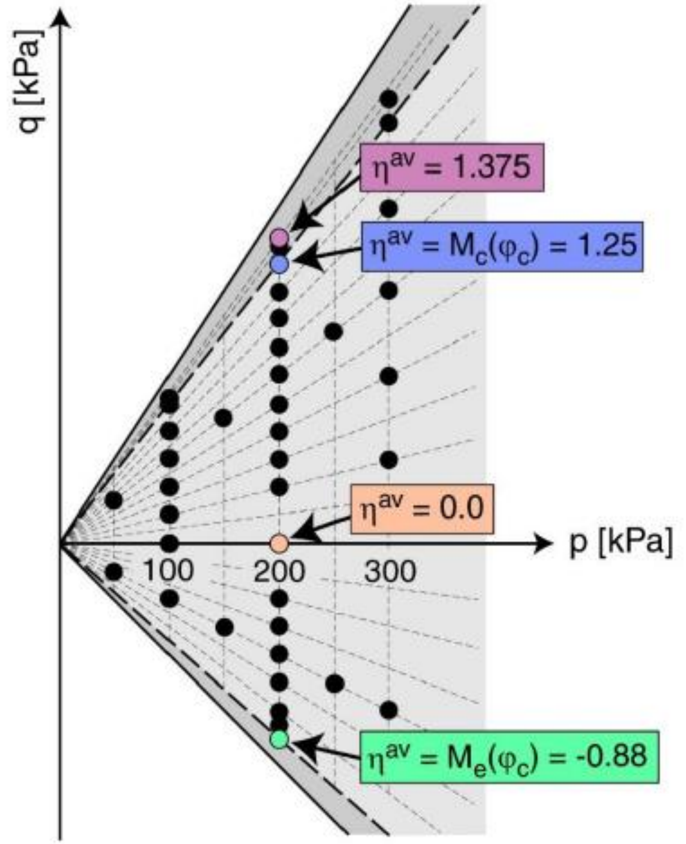


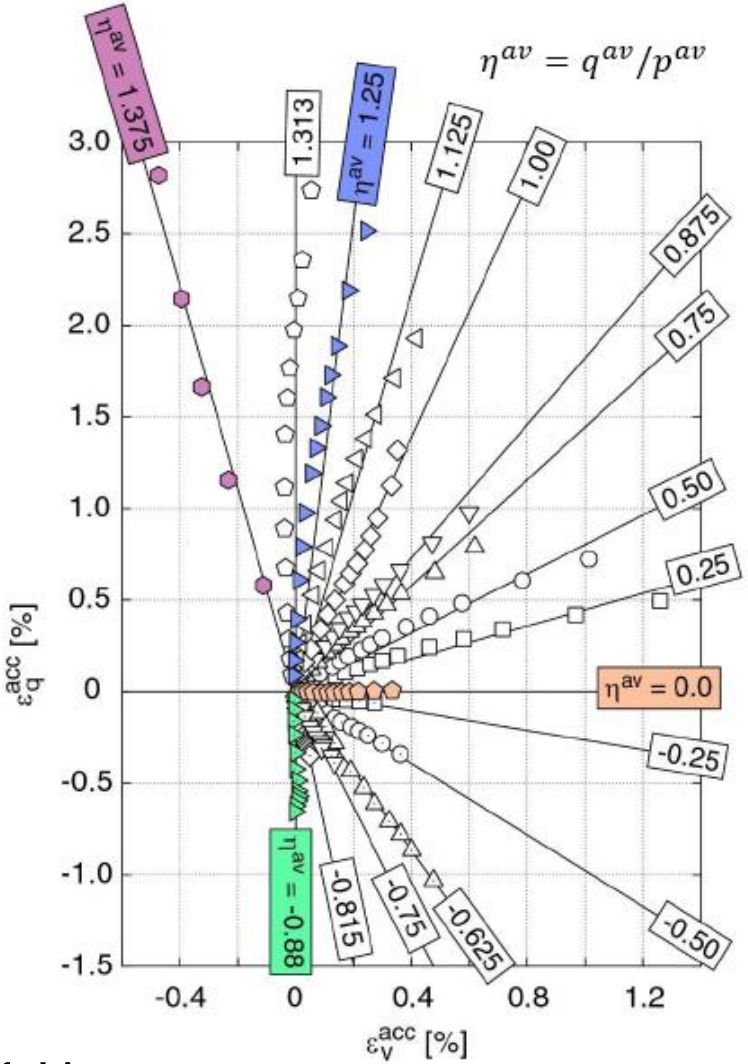
Reduction of C_{ampl} in the case of grains with high angularity because the grains get easily caught each other and under high pressures a transition from Goddard contact (Cone/Sphere) to Herz contact (Sphere/Sphere) takes place

→ Less pronounced amplitude dependence and opposite pressure dependence with increasing angularity of the grains

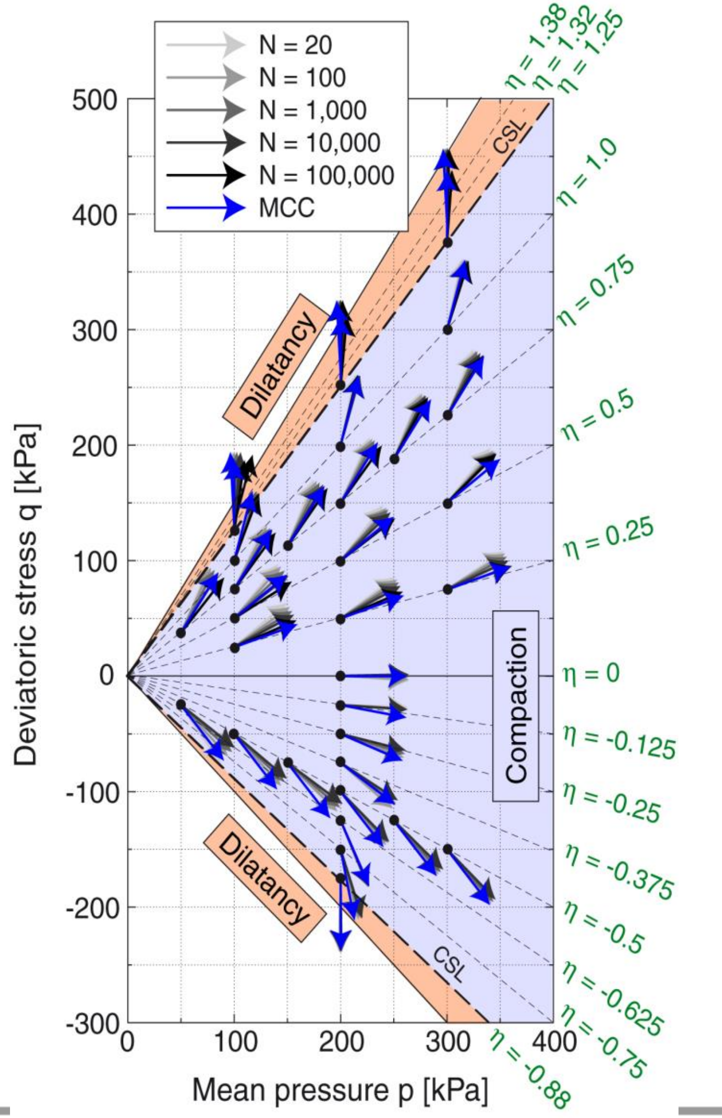
High cycle accumulation model

Calibration based on drained cyclic triaxial tests – direction of accumulation





$$\frac{\dot{\varepsilon}_v^{acc}}{\dot{\varepsilon}_q^{acc}} = \frac{M_c^2 - \eta^2}{2\eta}$$



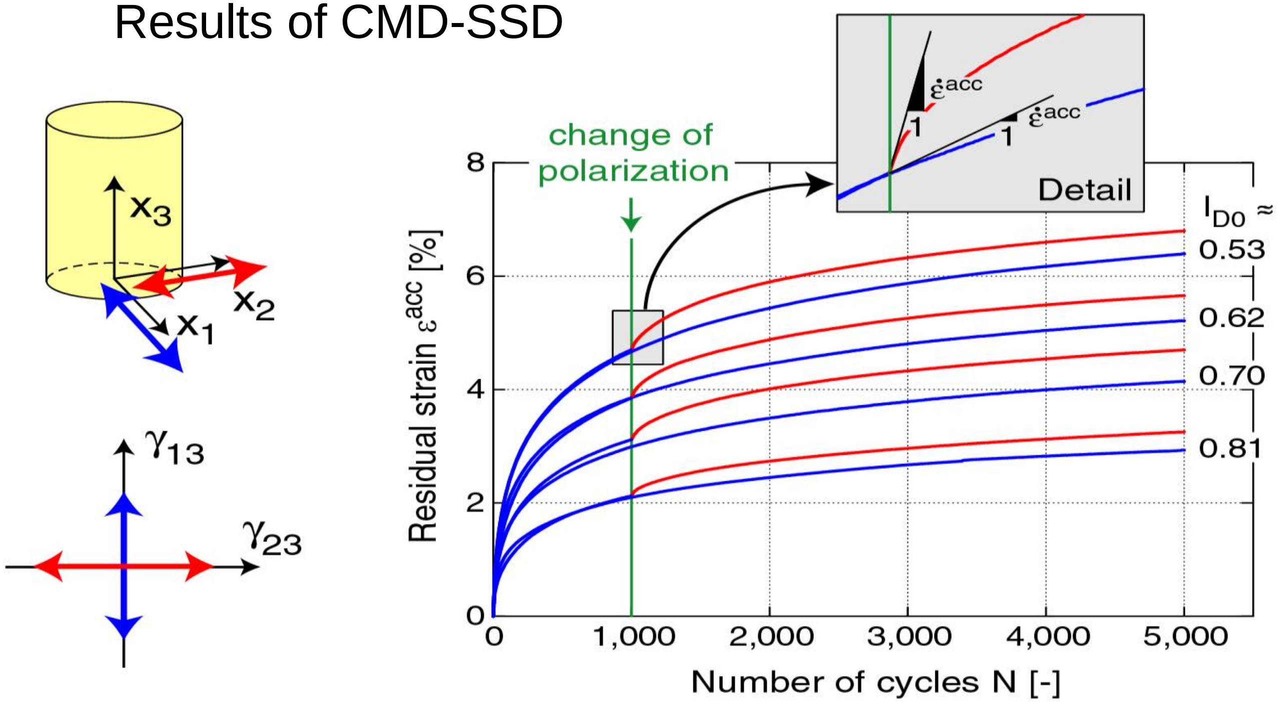
Wichtmann, T., Niemunis, A., Triantafyllidis, Th. (2006): Experimental evidence of a unique flow rule of non-cohesive soils under high-cyclic loading. Acta Geotechnica, Vol. 1, No. 1, pp. 59-73.

$f_{loading} = 1$ Hz

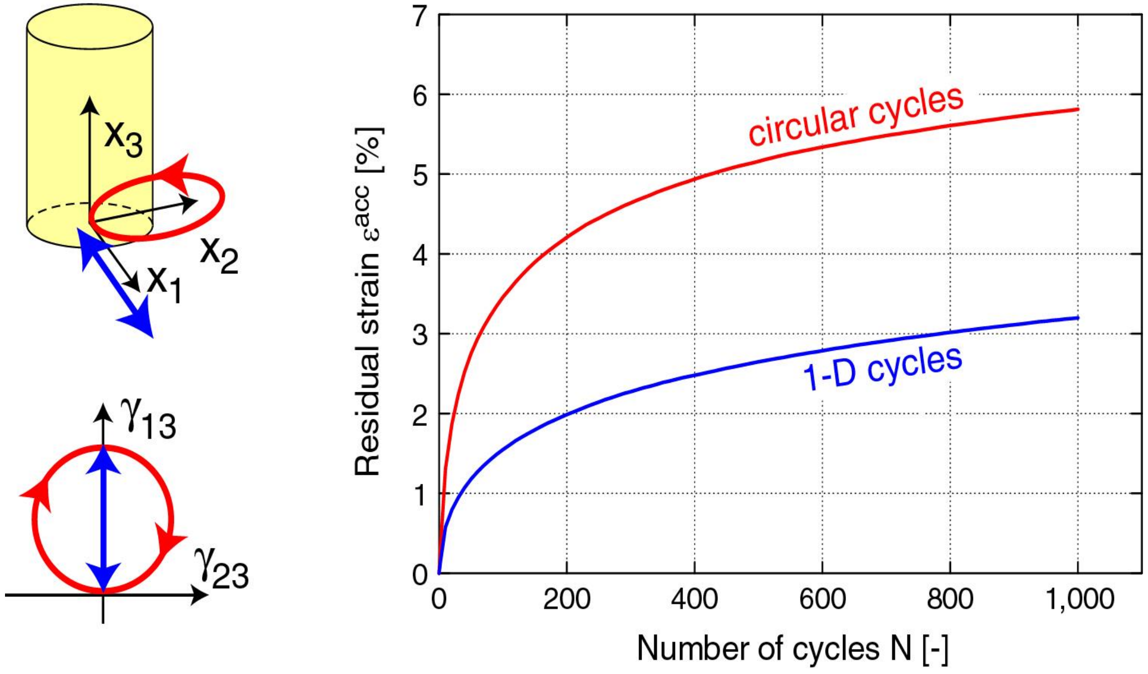
Problems associated with the offshore wind turbines

- Wind and wave direction as well as amplitude may change
- Any change in direction produces additional accumulations
- Accumulation effects with different amplitudes and cyclic preloading efects are needed.

Results of CMD-SSD



Amplitude in more than one dimension???



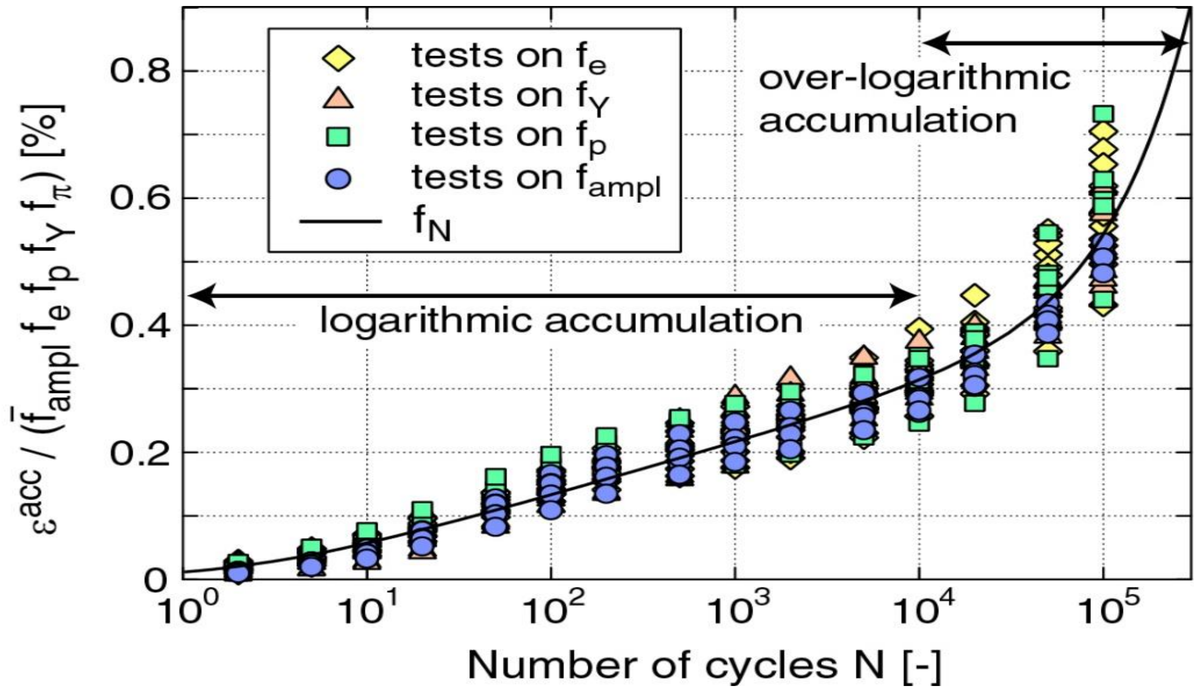
$$\dot{\boldsymbol{\sigma}} = \mathsf{E} : (\dot{\boldsymbol{\varepsilon}} - f_{\mathrm{ampl}}\ \dot{f}_N\ f_p\ f_Y\ f_e\ f_\pi\ \mathbf{m} - \dot{\boldsymbol{\varepsilon}}^{\mathrm{pl}})$$

Problems associated with the offshore wind turbines

HCA-Model $\dot{\boldsymbol{\sigma}} = \mathsf{E} : (\dot{\boldsymbol{\varepsilon}} - f_{\mathrm{ampl}} \dot{f}_N f_p f_Y f_e f_\pi \mathbf{m} - \dot{\boldsymbol{\varepsilon}}^{\mathrm{pl}})$

Influence of the number of cycles / cyclic preloading

Wichtmann (2005):



Accumulation model:

$$f_N = C_{N1} \left[\ln \left(1 + C_{N2} N \right) + C_{N3} N \right]$$

C_{N1}, C_{N2}, C_{N3} material constants

Die new historiotropic variable g^A is defined with the function f_N :

$$\dot{f}_N = \dot{f}_N^A + \dot{f}_N^B$$

$$\dot{f}_N^A = C_{N_1} * C_{N_2} \exp\left(-\frac{g^A}{C_{N_1} f_{ampl}}\right)$$

$$g^A = \int f_{ampl} \dot{f}_N^A \, dN$$

$$\dot{f}_N^B = C_{N_1} * C_{N_3}$$

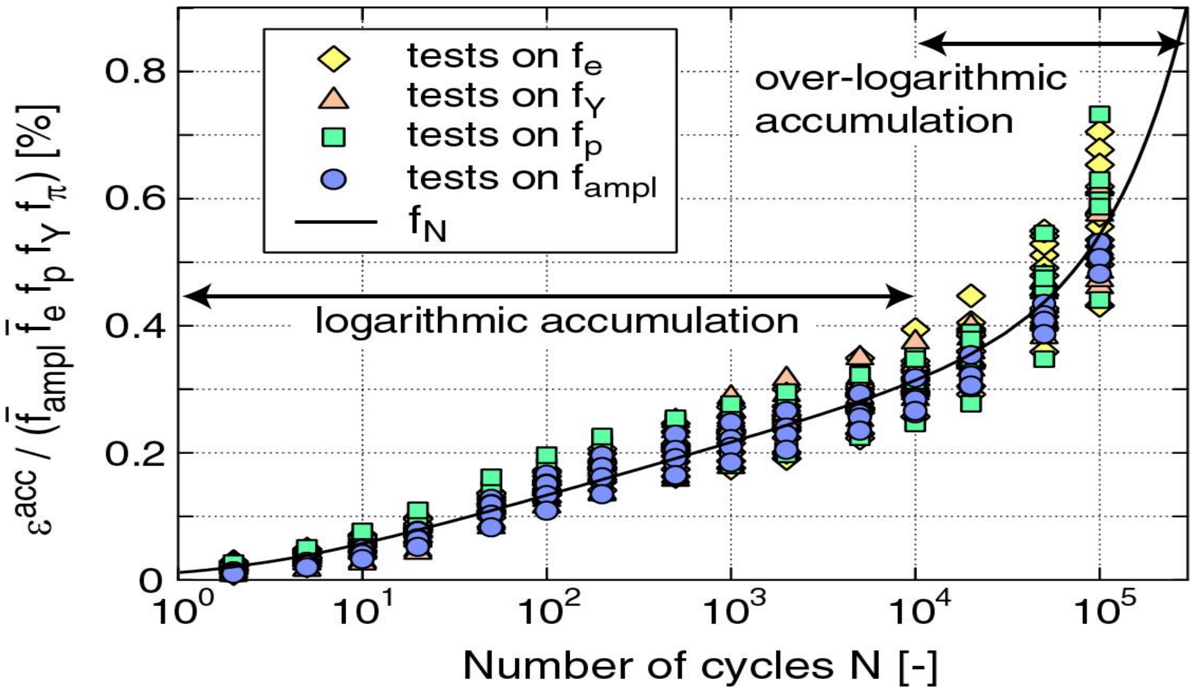
Inluence of amplitude and preloading

$$\dot{\boldsymbol{\sigma}} = \mathsf{E} : (\dot{\boldsymbol{\varepsilon}} - f_{\text{ampl}}\ \dot{f}_N\ f_p\ f_Y\ f_e\ f_\pi\ \mathbf{m} - \dot{\boldsymbol{\varepsilon}}^{\text{pl}})$$

Test results with only one cyclic amplitude is not sufficient for the solution of the serviceability we need a general form
The number of cycles must be regarded together with the amplitude.

Influence of the number of cycles / cyclic preloading

$$f_N = C_{N1}\left[\ln(1 + C_{N2}N) + C_{N3}N\right]$$



Problems:

1. Number of cycles N alone should not be used as a state variable in accumulation models, since it contains no information about the amplitude of the cycles

→ **new state variable** $g^A = f(\varepsilon^{\text{ampl}}, N)$

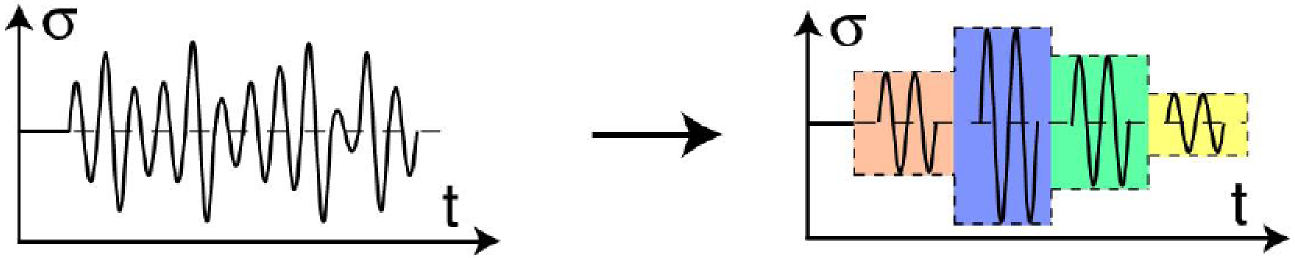
$$g^A = \int f_{\text{ampl}}\ \dot{f}_N^A\ \mathrm{d}N$$

$$\dot{f}_N^A = C_{N1}C_{N2}\exp\left(-\frac{g^A}{C_{N1}\ f_{\text{ampl}}}\right)$$

2. Initial value N_0 or g_0^A in situ (so-called cyclic preloading) is unknown

Parametrs affecting strain accumulation

Varying amplitude



- For a calculation with the HCA model cycles with different amplitudes have to be grouped into packages of cycles with same amplitude
- Is such bundling conservative?

*Wichtmann, T., Niemunis, A., Triantafyllidis, Th. (2010):
Strain accumulation in sand due to drained cyclic loading: on the effect of monotonic and cyclic preloading (Miner's rule). Soil Dynamics and Earthquake Engineering, Vol. 30, No. 8, pp. 736-745.*

*Wichtmann, T., Triantafyllidis, Th. (2017):
Strain accumulation due to packages of cycles with varying amplitude and/or average stress - on the bundling of cycles and the loss of the cyclic preloading memory. Soil Dynamics and Earthquake Engineering, Vol. 101, pp. 250-263.*

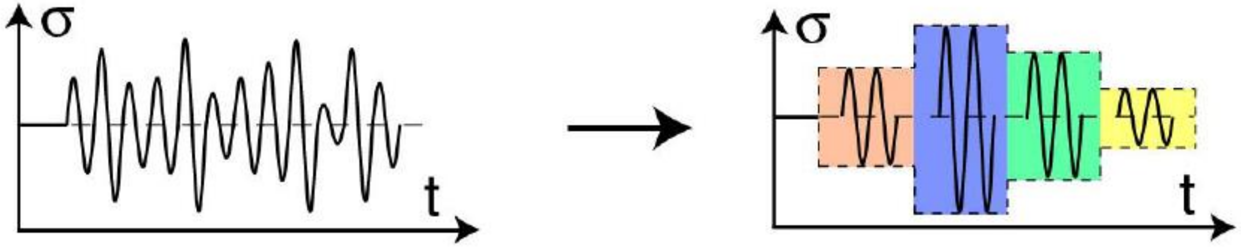
Wind loading is not of deterministic but rather of stochastic nature with varying average value and amplitude.

The simpliest case is the one with constant average stress level and varying amplitude. In this case the Miner‘s rule apply wherby the sequence of loading is not of importance.

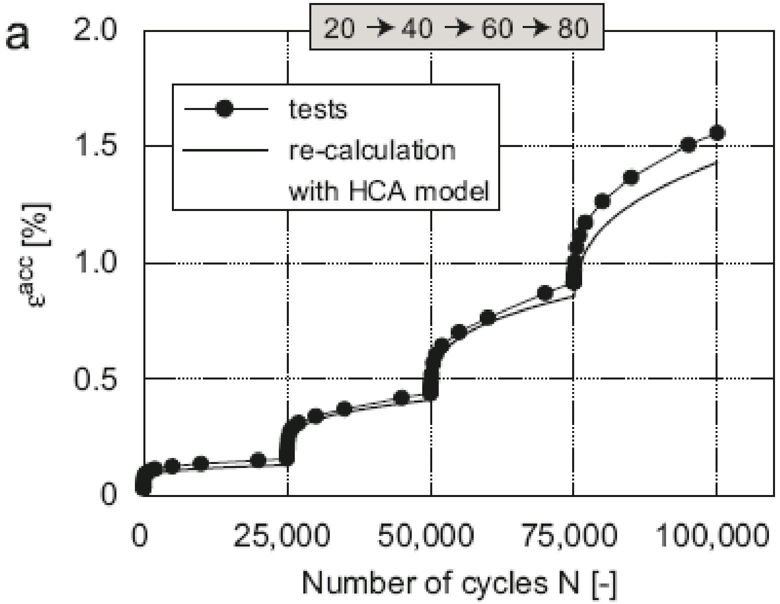
In case of strong average pressure variation a part of the preloading memory is lost (Miner‘s rule is no more applicable).

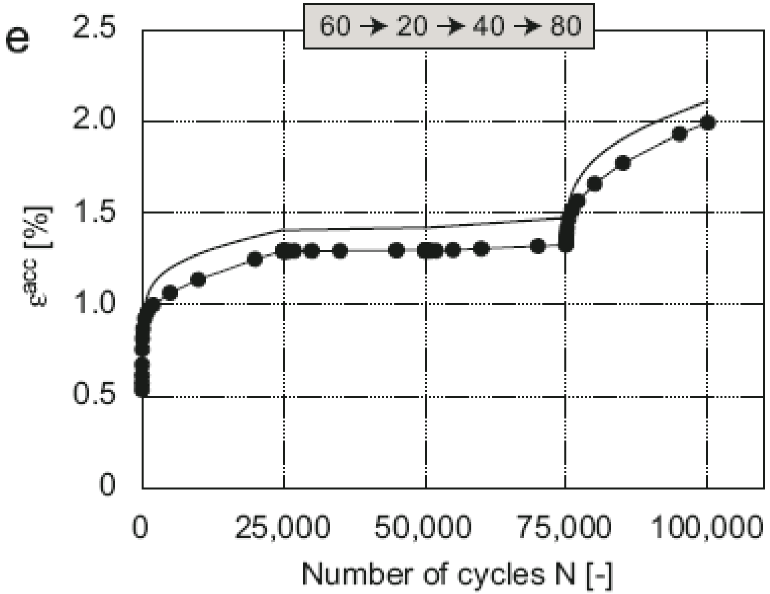
Sequence of loading on strain accumulation

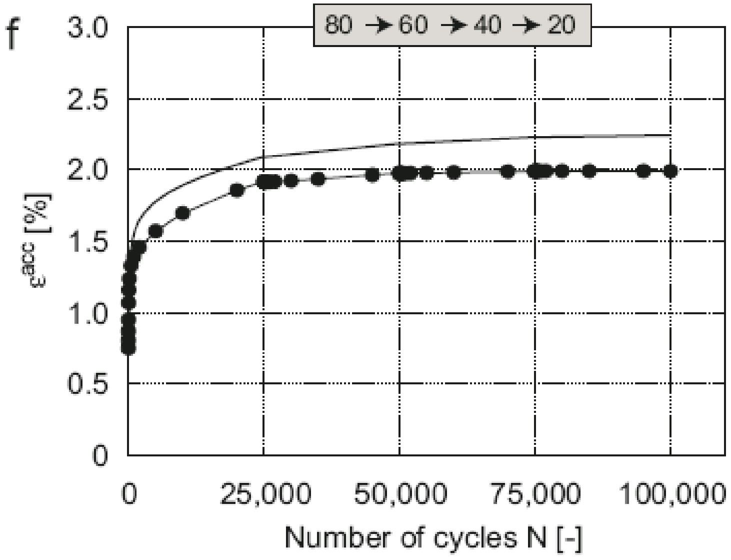
$p^{av} = 200$, η^{av} 0,75 , $I_{d0} = 0,60$



Parameter	Value
C_{ampl}	1.76
C_e	0.53
e_{ref}	0.874
C_p	0.42
C_Y	2.06
$C_{N\ 1}$	3.6×10^{-4}
$C_{N\ 2}$	0.42
$C_{N\ 3}$	5.0×10^{-4}

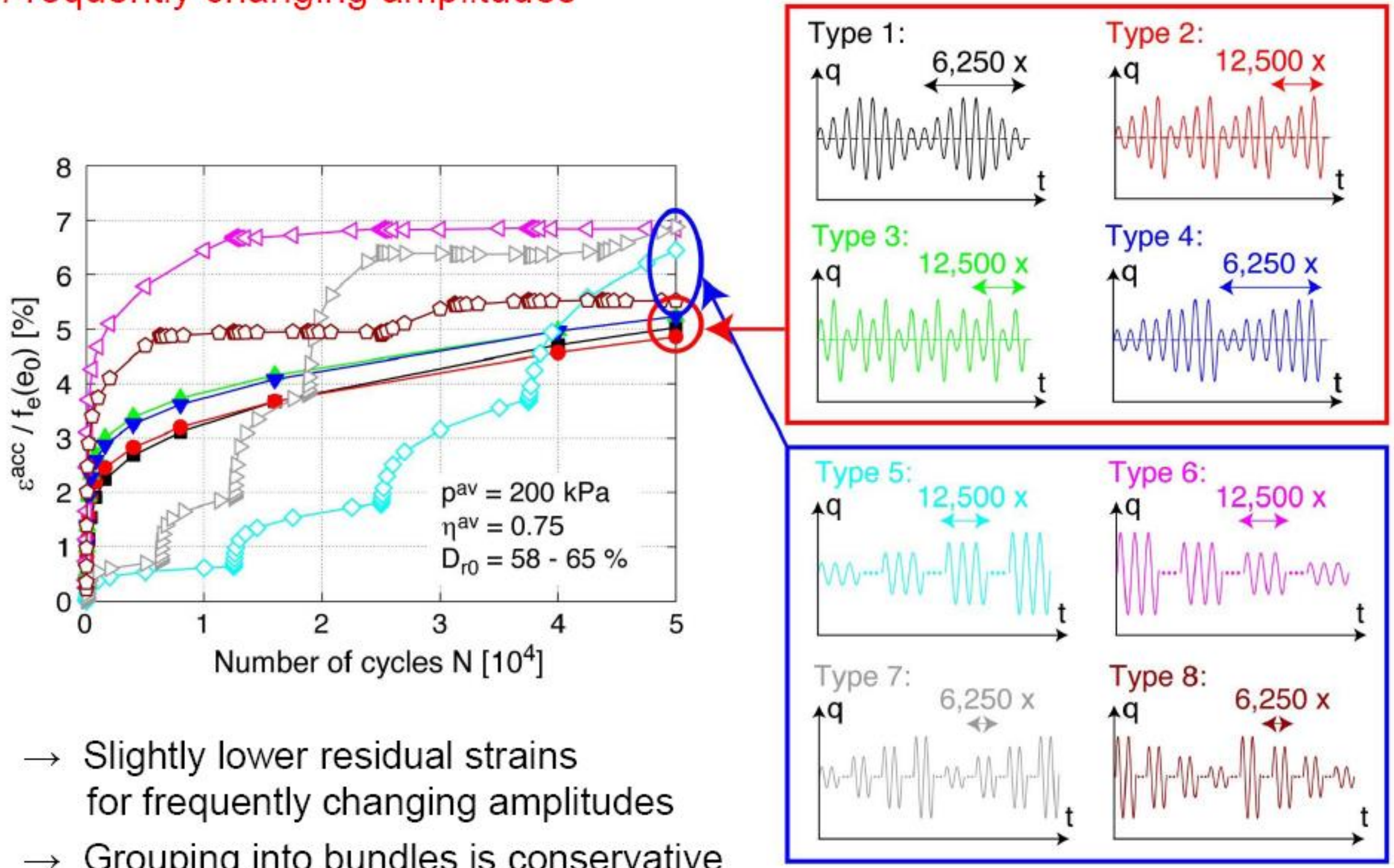






Parametrs affecting strain accumulation

Frequently changing amplitudes



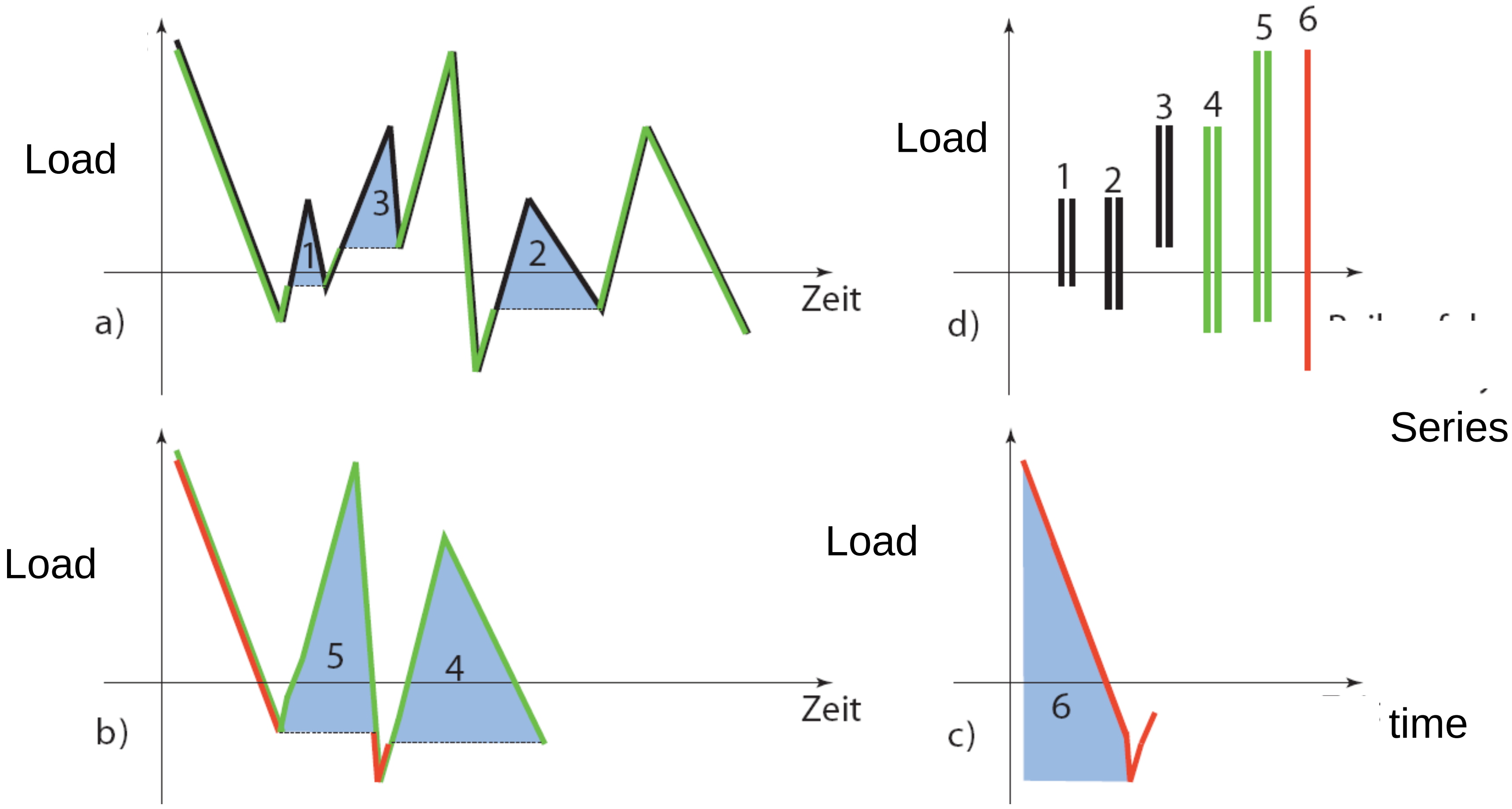
→ Slightly lower residual strains for frequently changing amplitudes

→ Grouping into bundles is conservative

For constant average stress p^{av} the grouping into packages (bundles) leads to slightly higher accumulation of strains Example for N =50000 in total but different sequences of loading

The start with the highest aplitude in the majority of studied cases in the model resulted to the maximum of accumulated strains

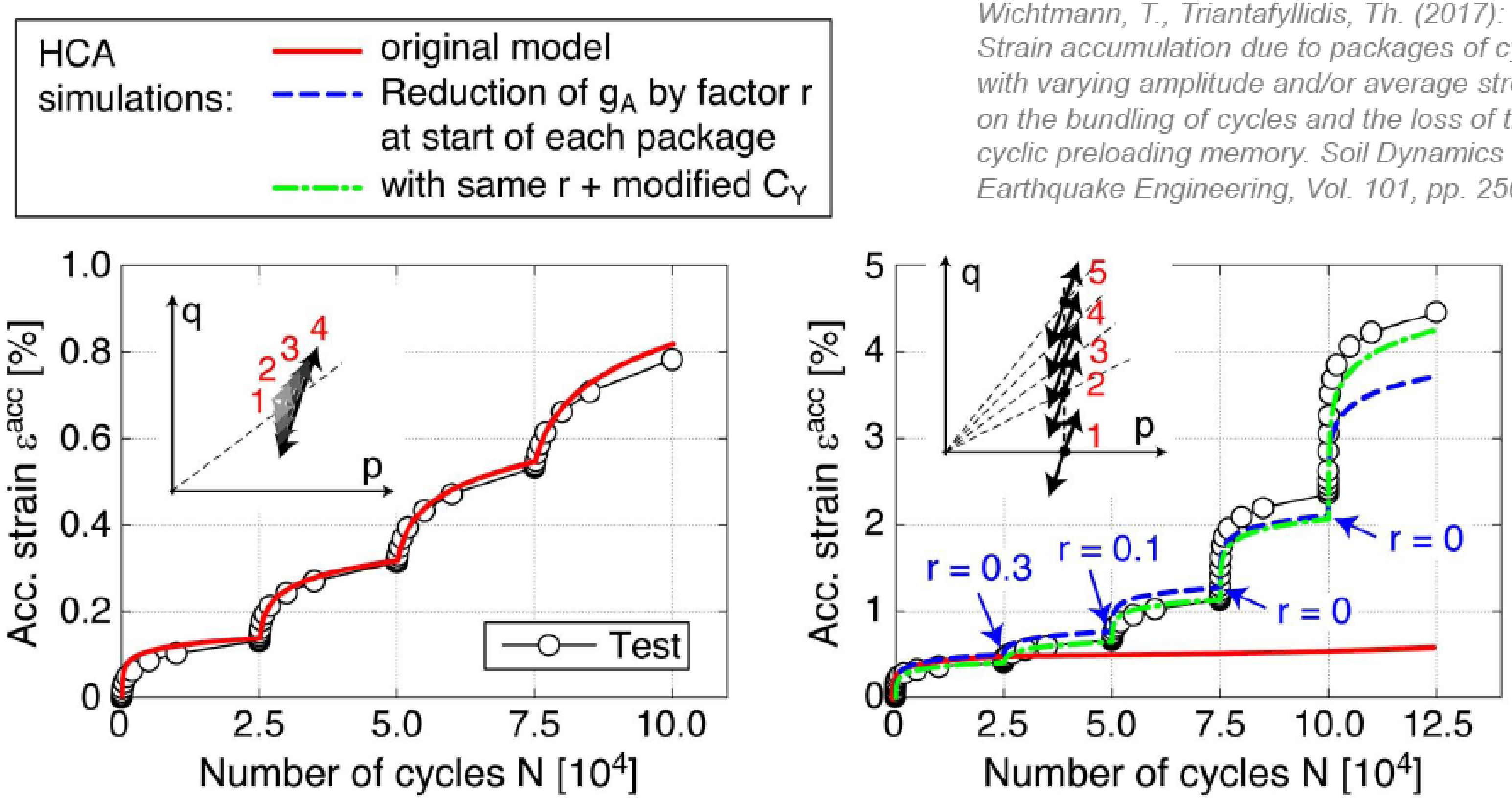
Conversion of a stochastic Signal as a series of bandles of cycles



In the general case of varying average stress and amplitude the Rainflow counting method can applied using half cycles

Parameters affecting strain accumulation

Monotonic loading phases between bundles of cycles applied at different average stresses – loss of cyclic preloading memory



Wichtmann, T., Triantafyllidis, Th. (2017): Strain accumulation due to packages of cycles with varying amplitude and/or average stress - on the bundling of cycles and the loss of the cyclic preloading memory. Soil Dynamics and Earthquake Engineering, Vol. 101, pp. 250-263.

An extension of the HCA model is possible in combination with the impicit model used for the determination of the strain amplitude

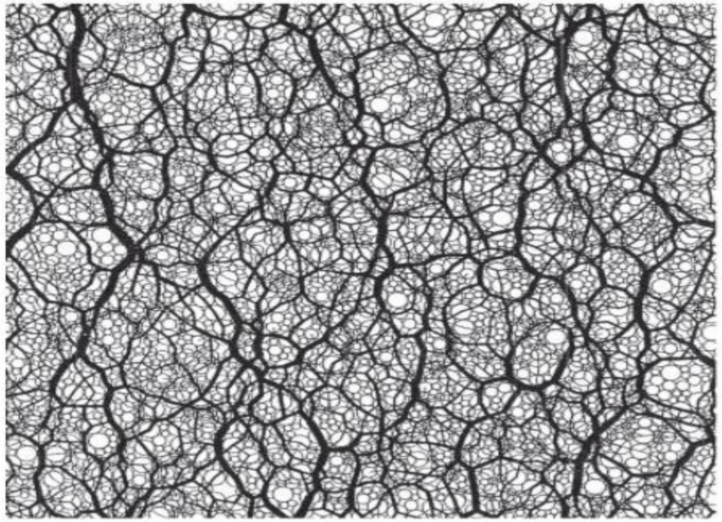
(see further WS presentations for advanced modelling)

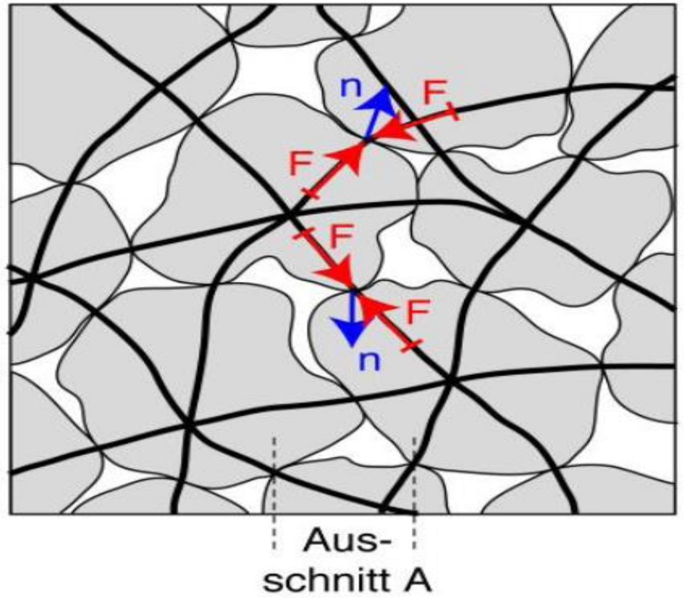
→ HCA calculation procedure has to be extended by a „forgetting mode“

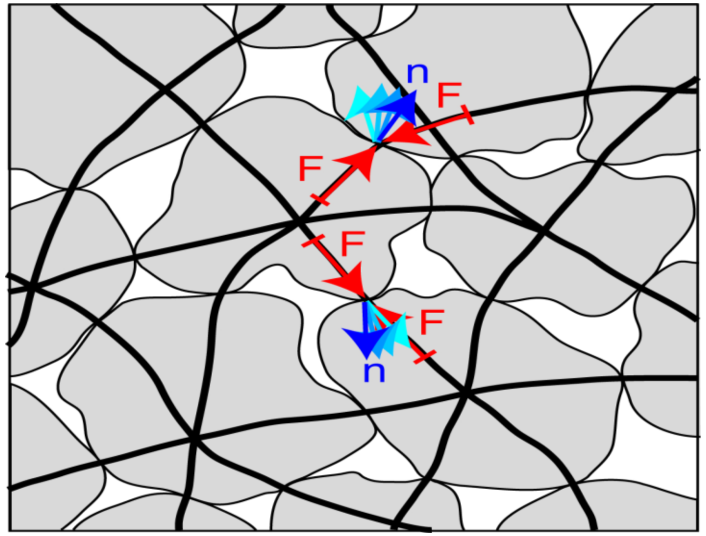
Analogy to the fractal structures of the force interparticle chains

Force interparticle chains depend on the surface angularity of grains

→ fractal structure in the stochastic sense



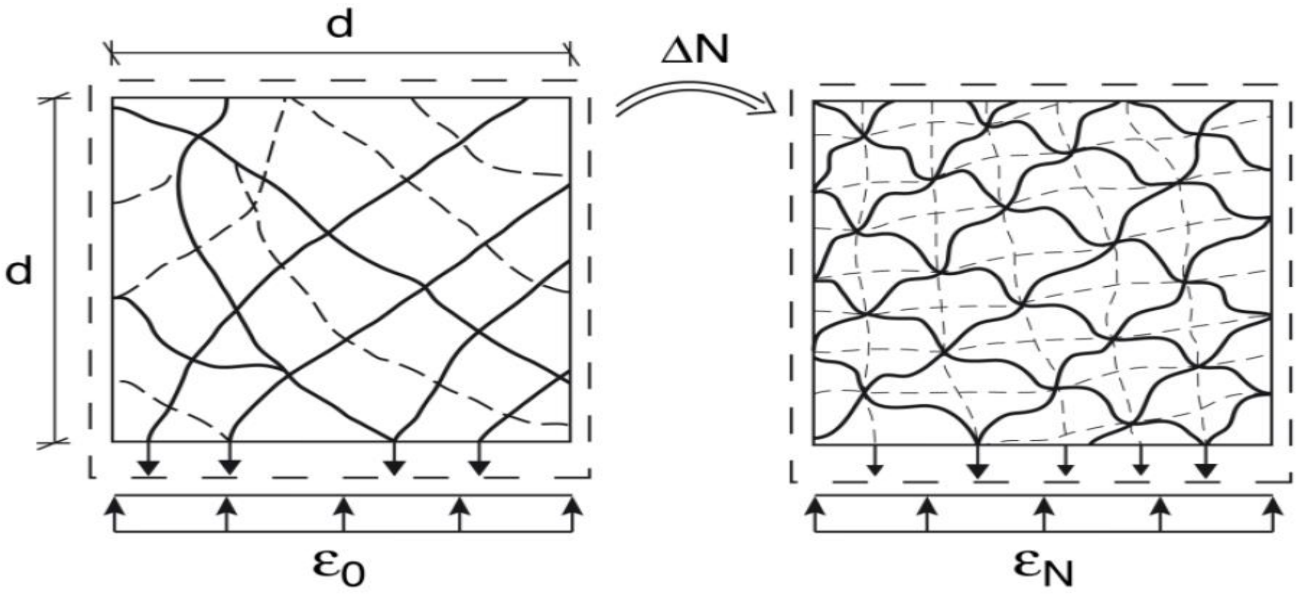




Cyclic loading lead to changes of the grain contacts
→ changes in direction and intensity of the intergranular forces with the number of cycles

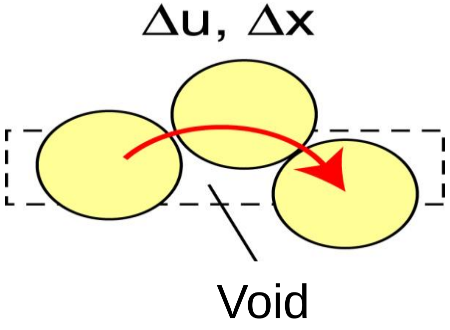
Analogy to the fractal structures of the force interparticle chains

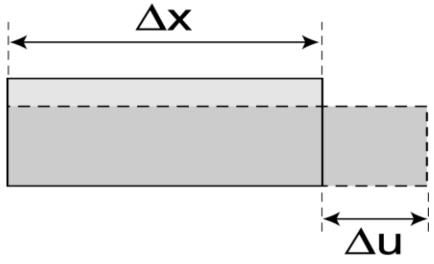
- The structure of the force chains can not described via homogenisation to a continuum. A better description with the fractional calculus is possible (fractional derivatives)
- Changes of the load chains due to the number of cycles has an influence on the strain accumulation :



$$\varepsilon = D_N^{\alpha} = \frac{\partial^{\alpha}\varepsilon}{\partial N^{\alpha}} \qquad \Delta\varepsilon(N) = I_{\Delta N}^{\alpha}\, D_{\Delta N}^{\alpha}\, \varepsilon = \varepsilon_N - \varepsilon_0$$

The strain path due to grain contacts is not the direct line between the elements in a continuum but they follow the chain of forces of the adjacent grains.
Displacements and paths can be described with a power function.





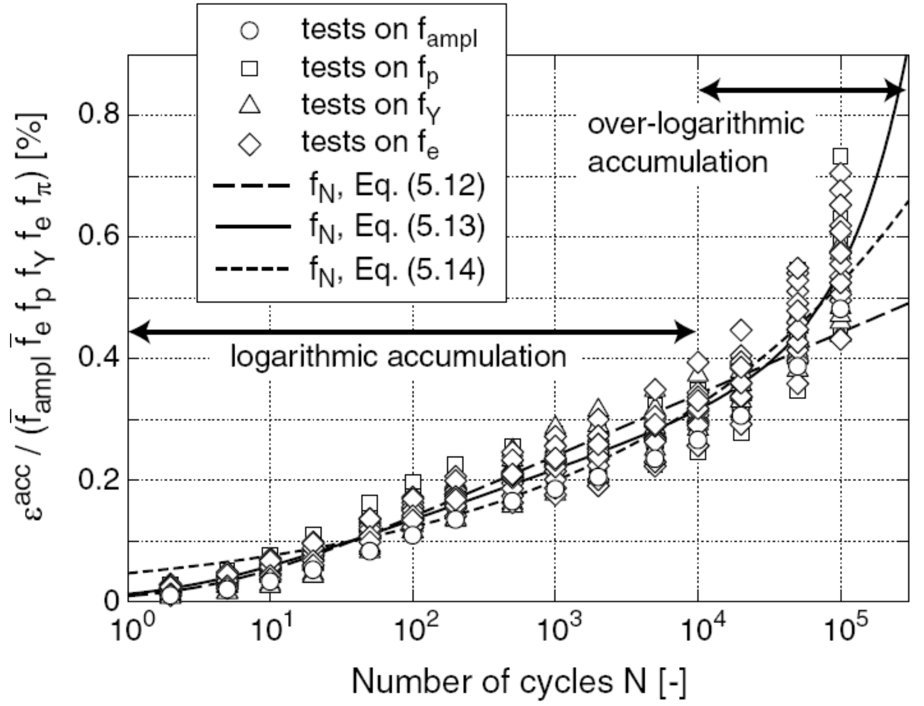
$$\varepsilon^{fract} = \frac{\partial u^{\alpha}}{\partial x^{\alpha}} \qquad \frac{\partial u}{\partial x} = \varepsilon$$

HCA-Model-rate of strain accumulation as a power function

$$f_N = C_{N1} \ln(1 + C_{N2} N) \quad (5.12)$$

$$f_N = C_{N1} \left[\ln(1 + C_{N2} N) + C_{N3} N\right] \quad (5.13)$$

$$f_N = C_{N1} N^{C_{N2}} \quad (5.14)$$



Power function

$$\varepsilon^{acc} = C_{N_1} \cdot N^{C_{N_2}}$$

$$\dot{\varepsilon}^{acc} = C_{N_1} C_{N_2} \cdot N^{-(1-C_{N_2})}$$

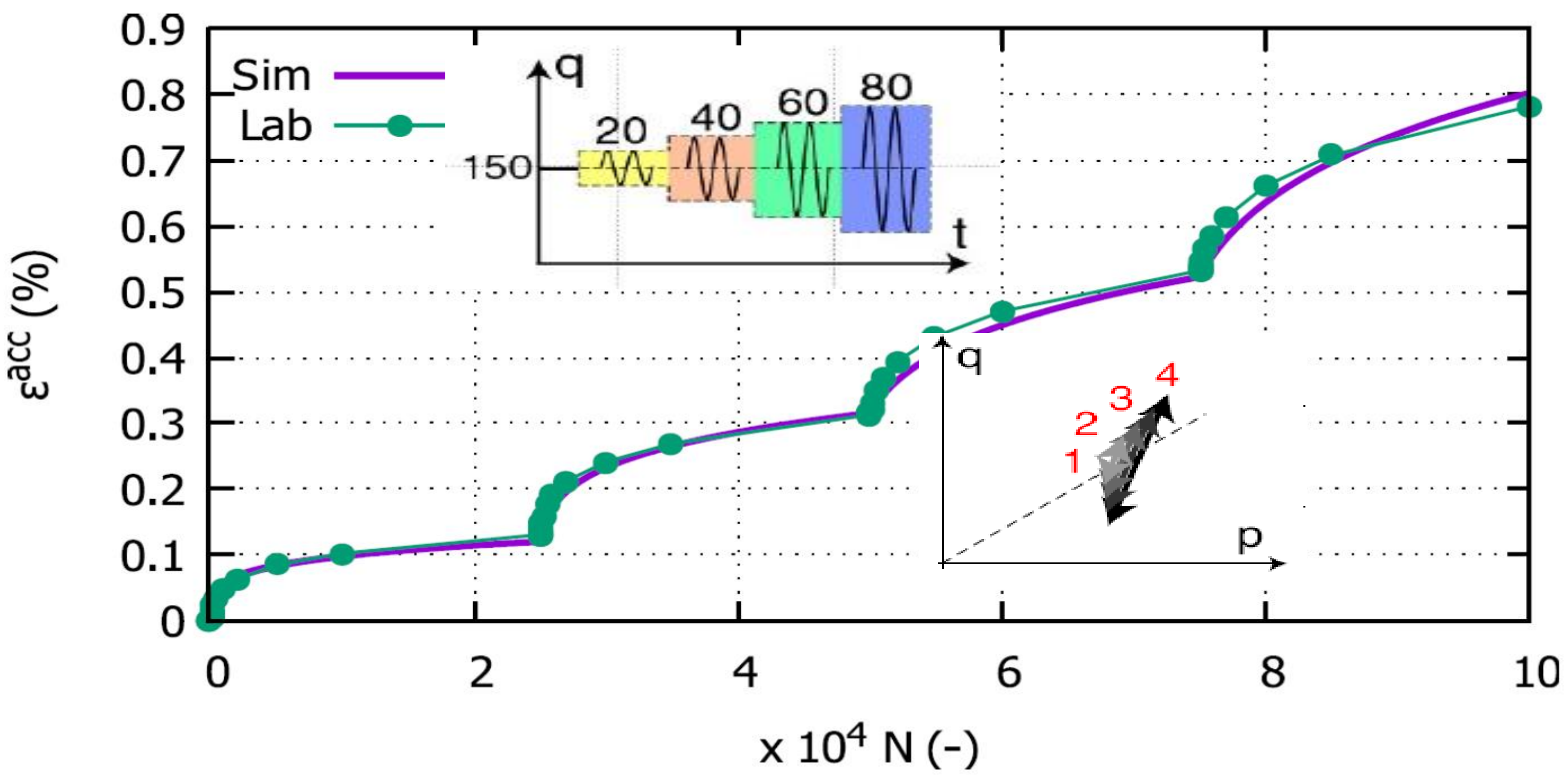
Rate of accumulation and fractal dimension do not depend on the number of cycles N (log-log graph)

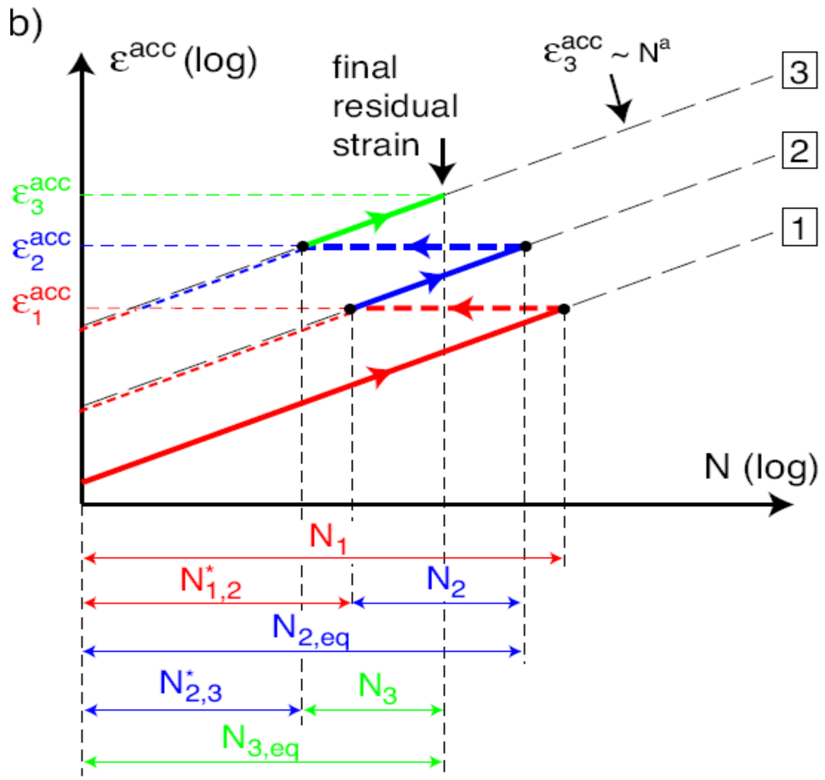
$$\frac{D^{C_{N_2}} \varepsilon^{acc}}{D N^{C_{N_2}}} = C_{N_2} \cdot C_{N_1} \cdot \Gamma(C_{N_2}) \quad \neq f(N)$$

(Gamma Function)

HCA-Model-for the accumulation using fractional calculus

Integration over the rate of accumulation with the numbers of cycles leads to the accumulation of deformation ε^{acc} for different amplitudes of loading but for the same average of stresses with the fractional calculus





$C_{N1} = 6{,}48 \cdot 10^{-4}$, $C_{N2} = 0{,}177$

Problems associated with the offshore wind turbines

Definition of the Amplitude in multidimensional cyclic loading

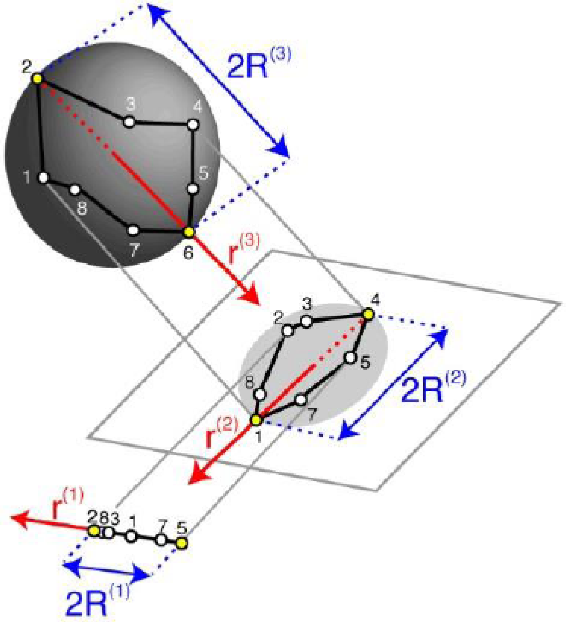
Multidimensional cyclic loading

- Multidimensional stress and strain paths result e.g. from moving loads (traffic)
- HCA model incorporates a multidimensional amplitude definition for 6D paths
- Strain amplitude ε^{ampl} is obtained from spans $2R^{(i)}$ and directions $\mathbf{r}^{(i)}$ determined from a series of projections of the strain loop from the 6D to 1D space

Niemunis (2003), Niemunis et al. (2005)

Niemunis, A., Wichtmann, T., Triantafyllidis, Th. (2005): A high-cycle accumulation model for sand. Computers and Geotechnics, Vol. 32, No. 4, pp. 245-263.

$$\varepsilon^{\text{ampl}} = \left\| \sum_{i=1}^{6} R^{(i)}\, \vec{\mathbf{r}}^{(i)} \otimes \vec{\mathbf{r}}^{(i)} \right\|$$



- Confirmed for 1D and 2D strain paths

Wichtmann, T., Niemunis, A., Triantafyllidis, Th. (2007): On the influence of the polarization and the shape of the strain loop on strain accumulation in sand under high-cyclic loading. Soil Dynamics and Earthquake Engineering, Vol. 27, No. 1, pp. 14-28.

- Purpose: Validation for up to 4D strain paths

In 3D Problems we need in general 6 components of the strains to describe the deformation behavior.
The amplitude is defined in 1D and therefore a new definition for the amplitude in order to capture its dimensionality s requiered.

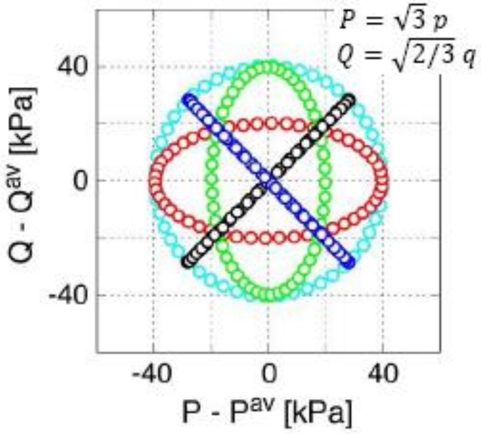
Subsequent projections of the 6D hypershpere of the largest strain spans to the lower dimensions will be used and the euclidian norm of the projections is used for the new amplitude definition

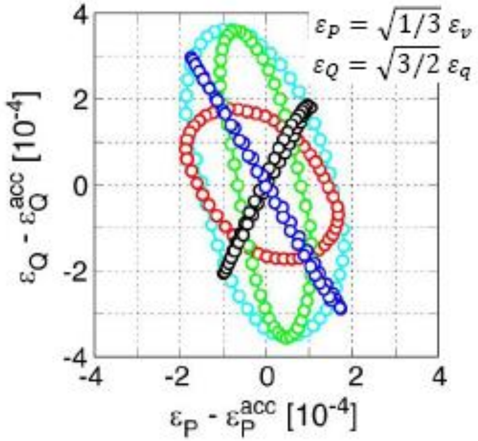
Is this definition correct or validated?

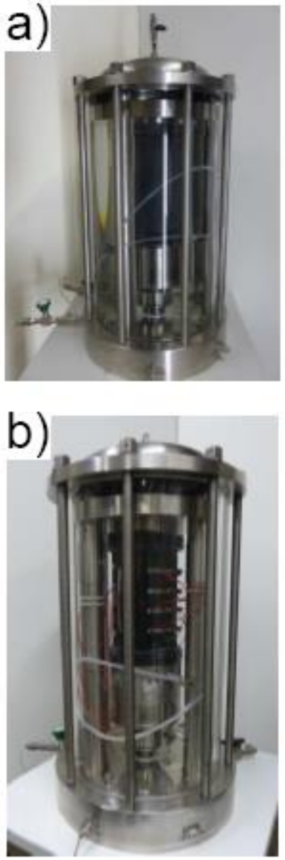
Parameters affecting the strain acumulation

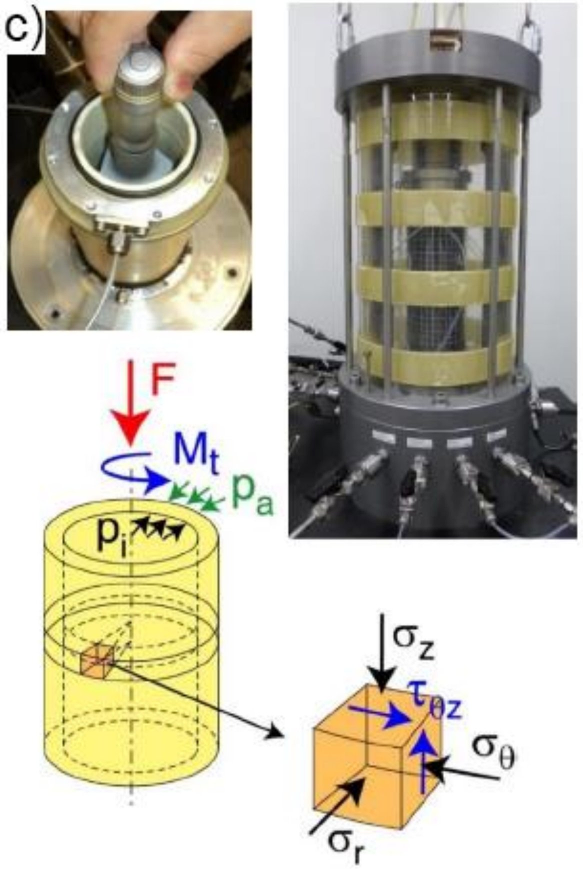
Multidimensional cycling loading

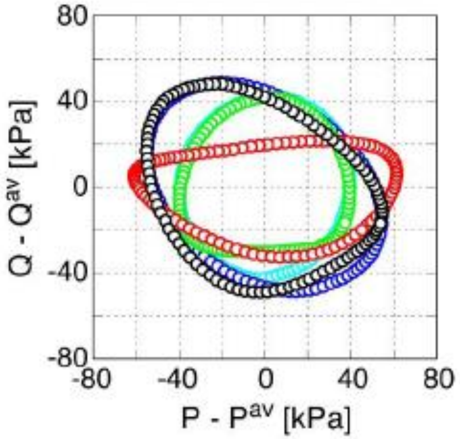
a) Cylindrical specimens (water saturated)
b) Cube shaped specimens with local measurement (dry)
c) Hollow cylinder specimens (water saturated)

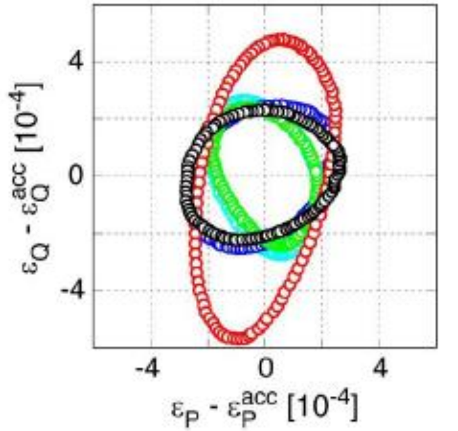












Stress tensor

$\sigma_{rr}\ \sigma_{r\theta}\ \sigma_{rz}$
$\sigma_{\theta r}\ \sigma_{\theta\theta}\ \sigma_{\theta z}$
$\sigma_{zr}\ \sigma_{z\theta}\ \sigma_{zz}$

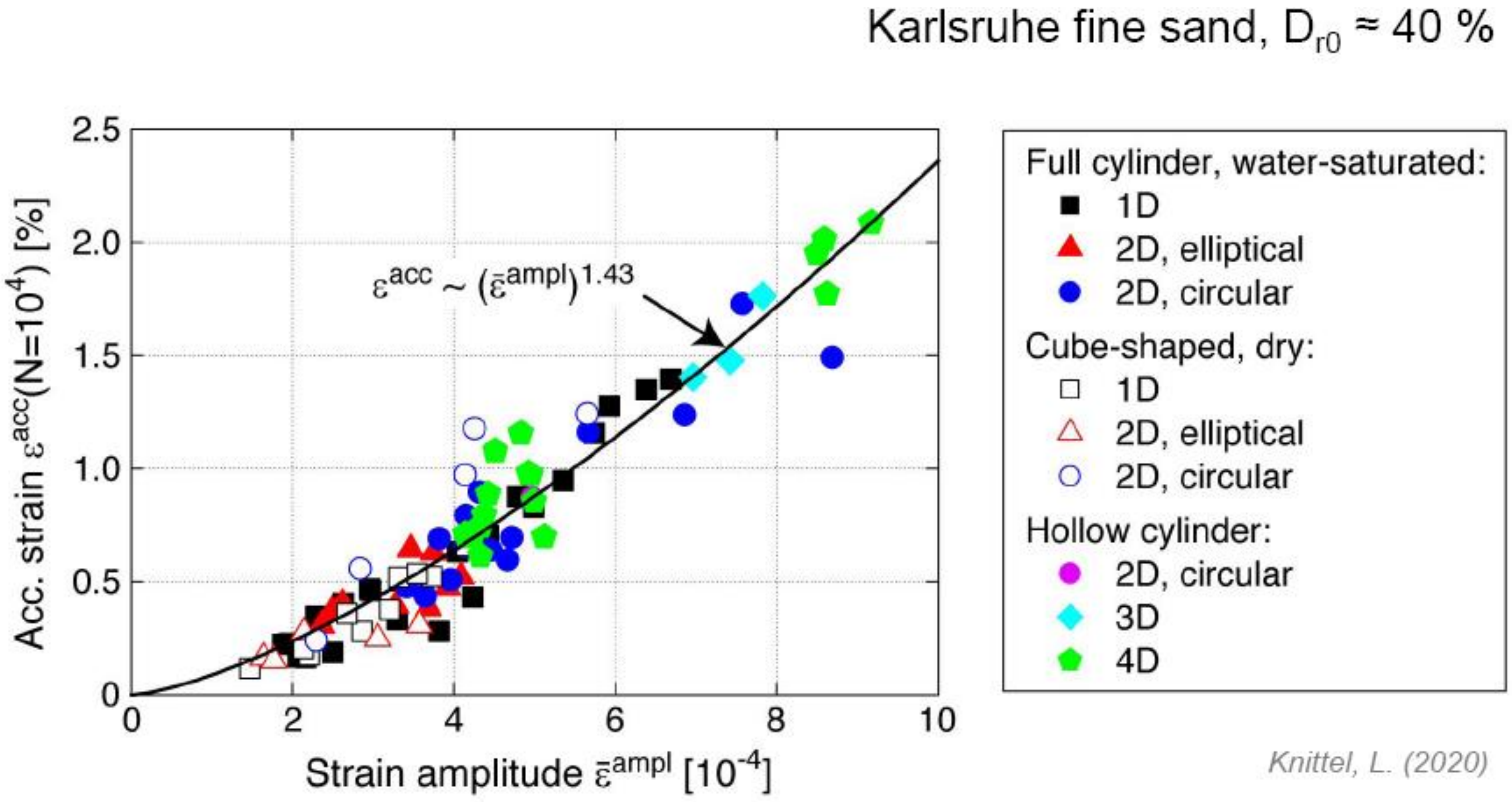
4 components can be varied

Dissertation
L. Knittel, KIT (2020)

Knittel, L. (2020): Behaviour of granular soils under multidimensional cyclic loading (in German), PhD thesis, KIT, Karlsruhe Issue No. 188

Parameters affecting the strain acumulation

Multidimensional cycling loading



Knittel, L. (2020)

Results:

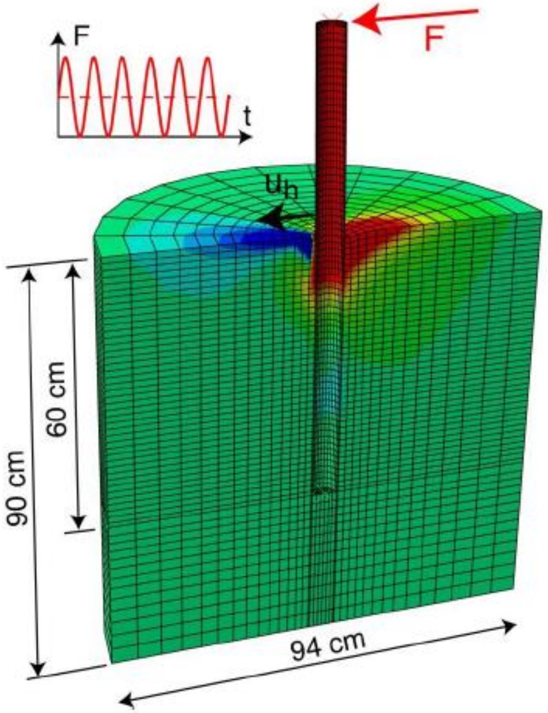
1) Using the definition of the multidimensional amplitude the experimental data for 1D to 4D strain paths lead to a single function f_{ampl}.
2) The definition of the multidimensional amplitude is validated for up to 4D strain paths
3) This validation is sufficient for the analysis of monopile or gravity foundations of WTs

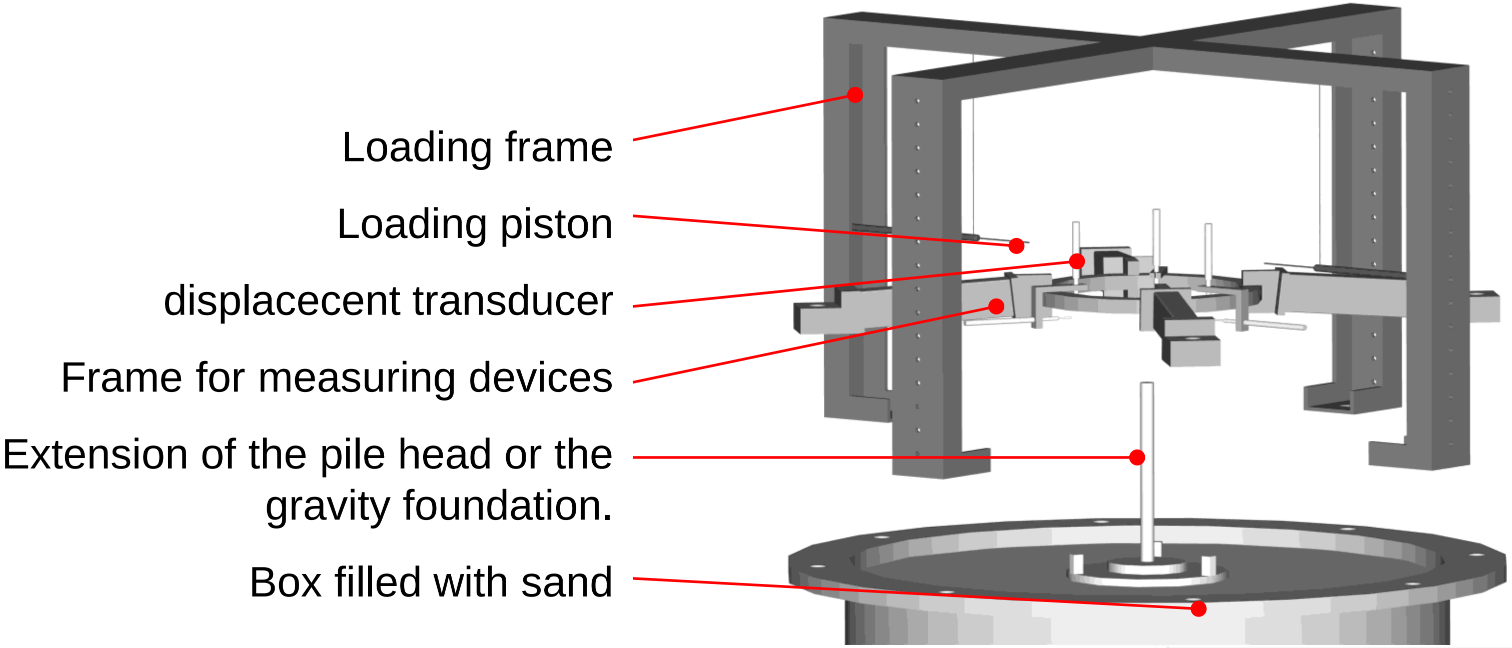
Validations of the HCA Model with model and in situ tests

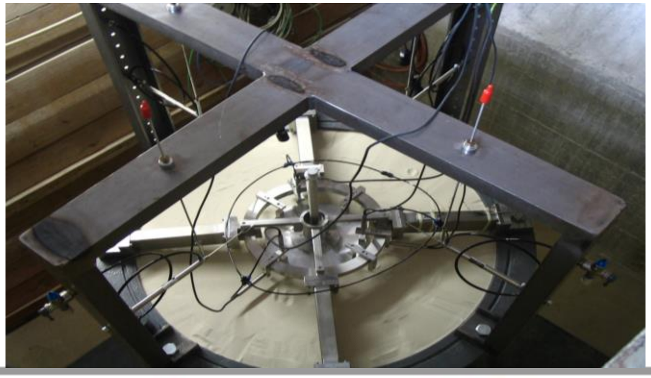
Testing box is a steel cylinder D = 94 cm, H = 143 cm with possible extensions for higher water level than the soil surface and mounting of the loading and measuring frames

- Sand dry, d_{50} = 0,164mm, C_u = 2,2, φ_c = 33°
- e_{min} = 0,67, e_{max} = 1,05, relative density $I_D \approx$ 90-93%
- Preparation methods: dry raining, moist tamping in layers, Soil mass ≈1550 kg

FE model:







Validations of the HCA Model with model and in situ tests

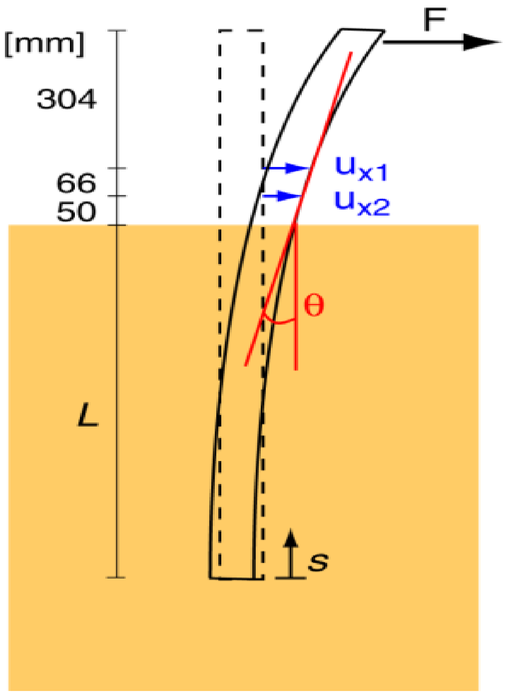
Dissertation
H. Zachert, KIT (2015)

Based on small-scale (1:50) model tests

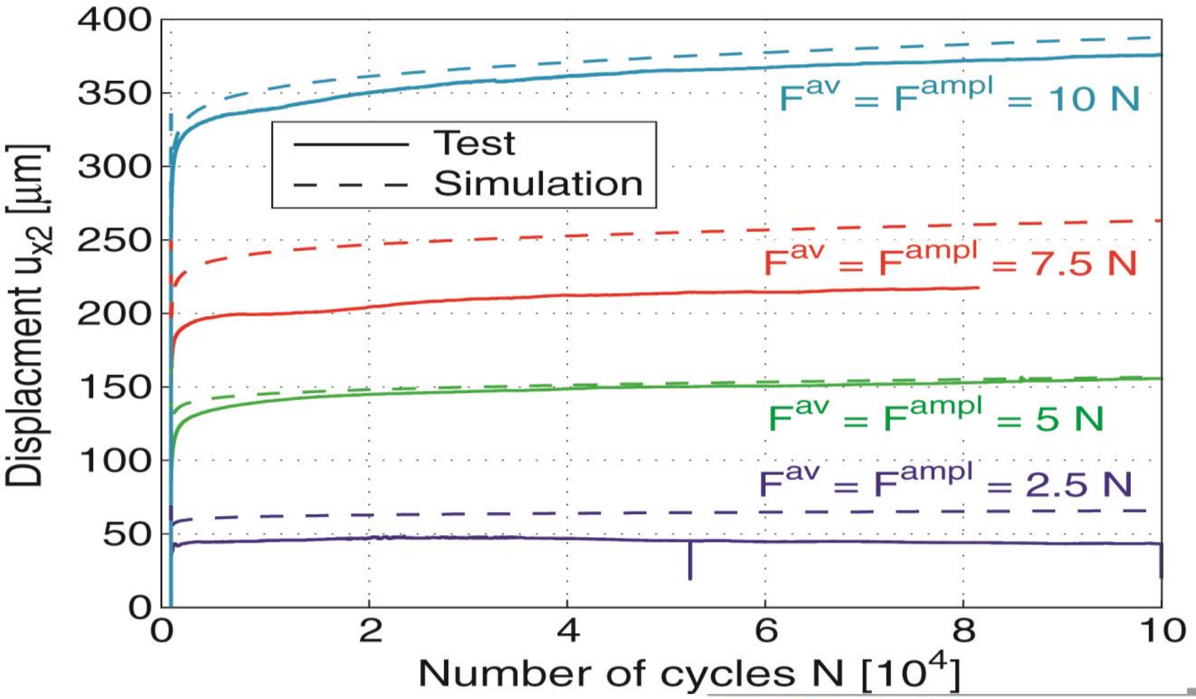
- Model tests on shallow and monopile foundations (1:50) with high-cyclic loading
- Aim: Inspection of the HCA model under clearly defined boundary conditions

Zachert, H. (2015): On the serviceability of foundations for offshore wind turbines (in German), PhD thesis, KIT, Karlsruhe, Issue No. 180

Monopiles:

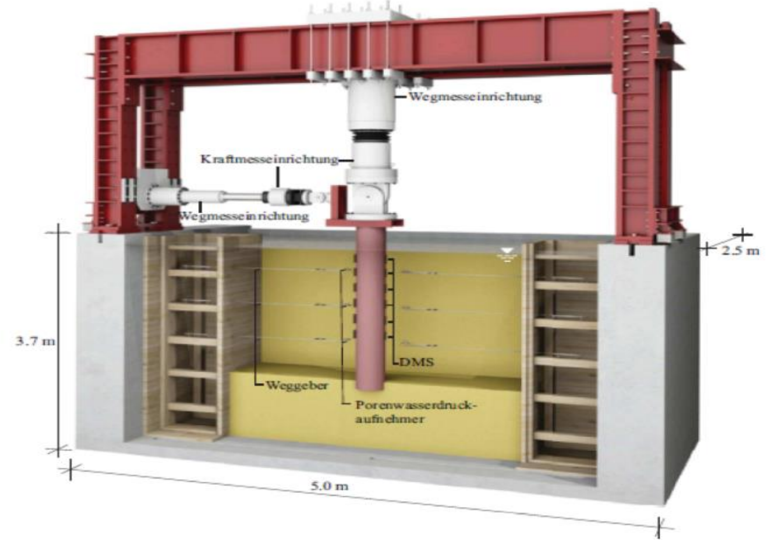


Bending moments in the pile due to accumulation effects under swelling loads



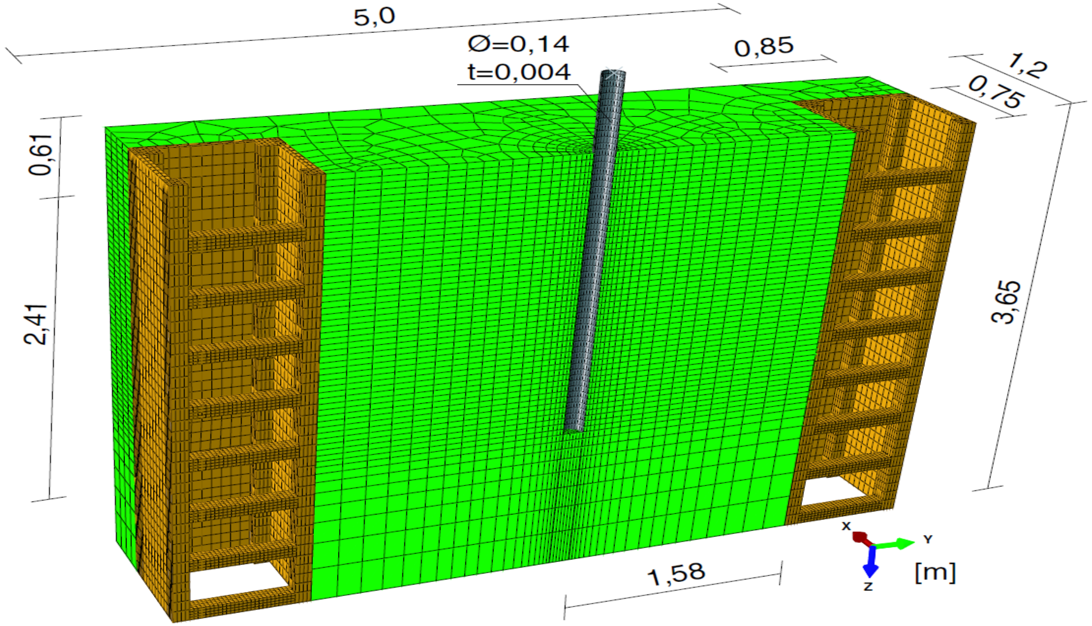
Good agreement between FE prediction and model test

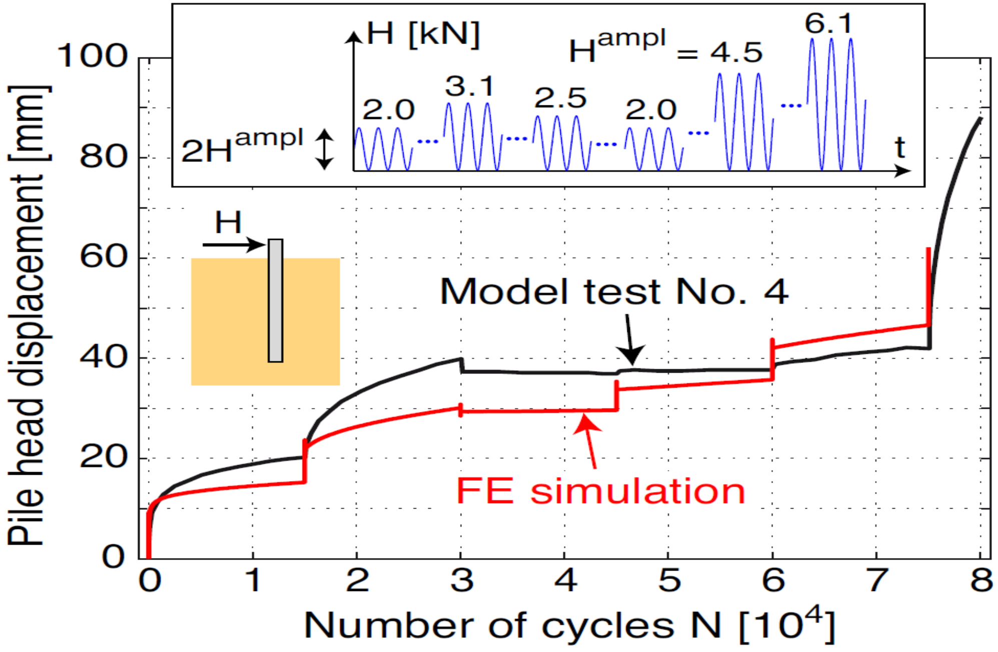
Validations of the HCA Model with model and in situ tests



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:



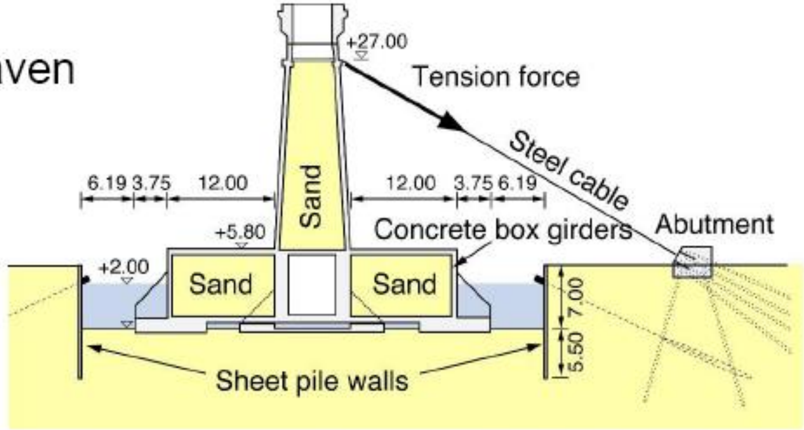


→ Good agreement between FE prediction and model test

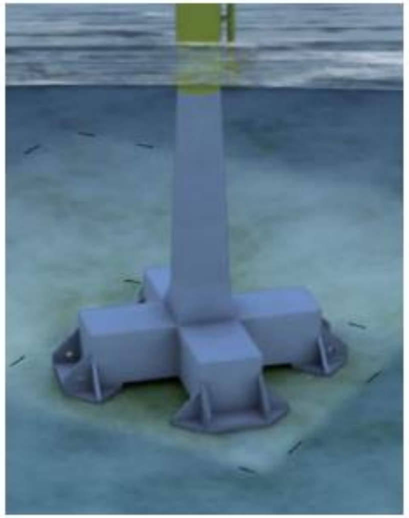
Validations of the HCA Model with model and in situ tests

Zachert, H., Wichtmann, T., Kudella, P., Triantafyllidis, Th. (2020): Inspection of a high-cycle accumulation model for sand based on recalculations of a full-scale test on a gravity base foundation for offshore wind turbines. Computers and Geotechnics, Vol. 126, Paper No. 103727

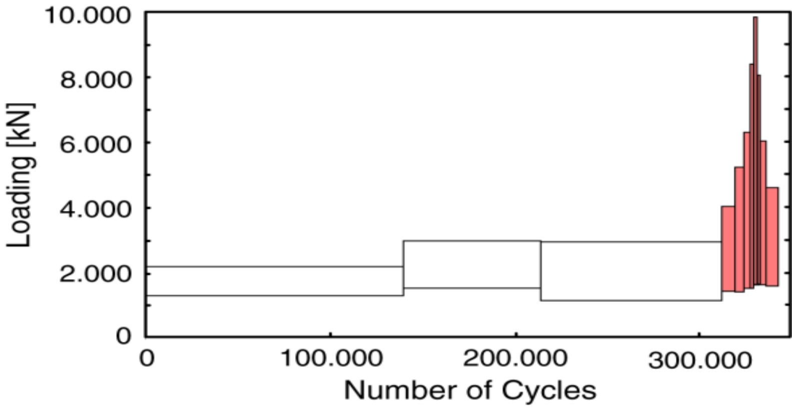
- Construction of a prototype near Cuxhaven
- Instrumentation of subsoil + foundation
- Simulation of 20 storm events by cyclic tension loads applied to tower (approx. 1.6 million cycles)



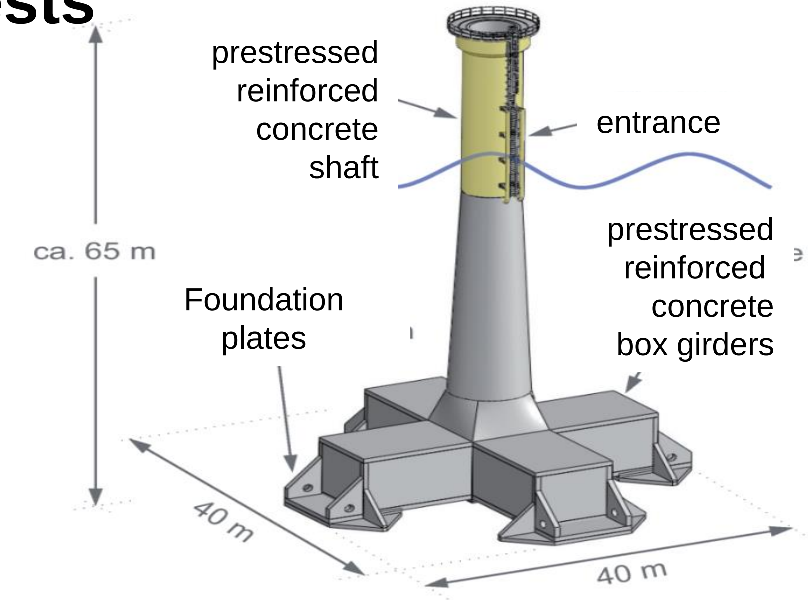
In situ test of Ed. Züblin AG on a shallow foundations on the shoreline in an excavation pit with back anchored sheet pile walls



First storm event after 320 K cycles

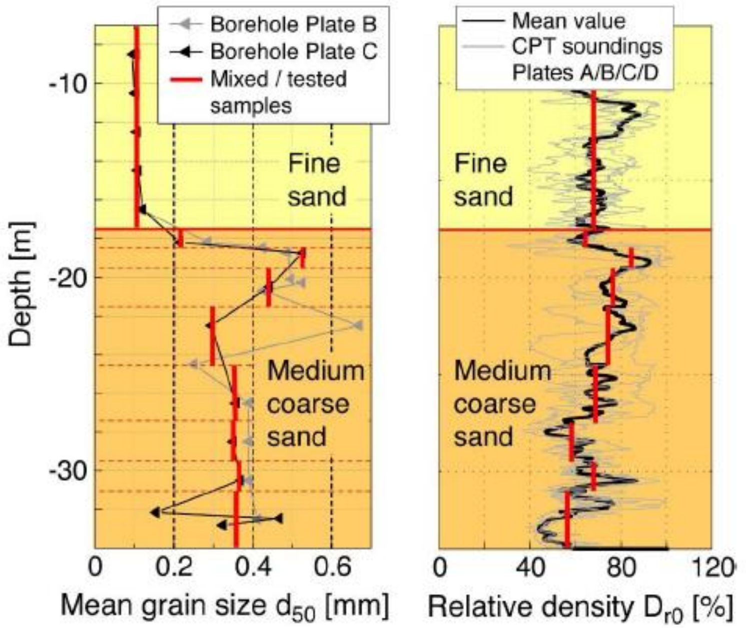


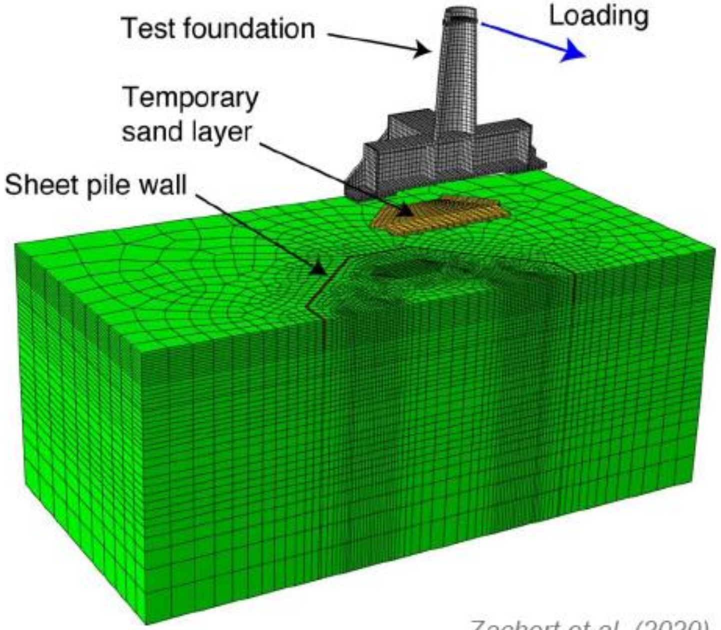
Validations of the HCA Model with model and in situ tests



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

- Determination of soil profile, constitutive parameters of the sand layers (from laboratory tests) and initial relative density (from CPT soundings)
- Generation of FE model considering the construction phases

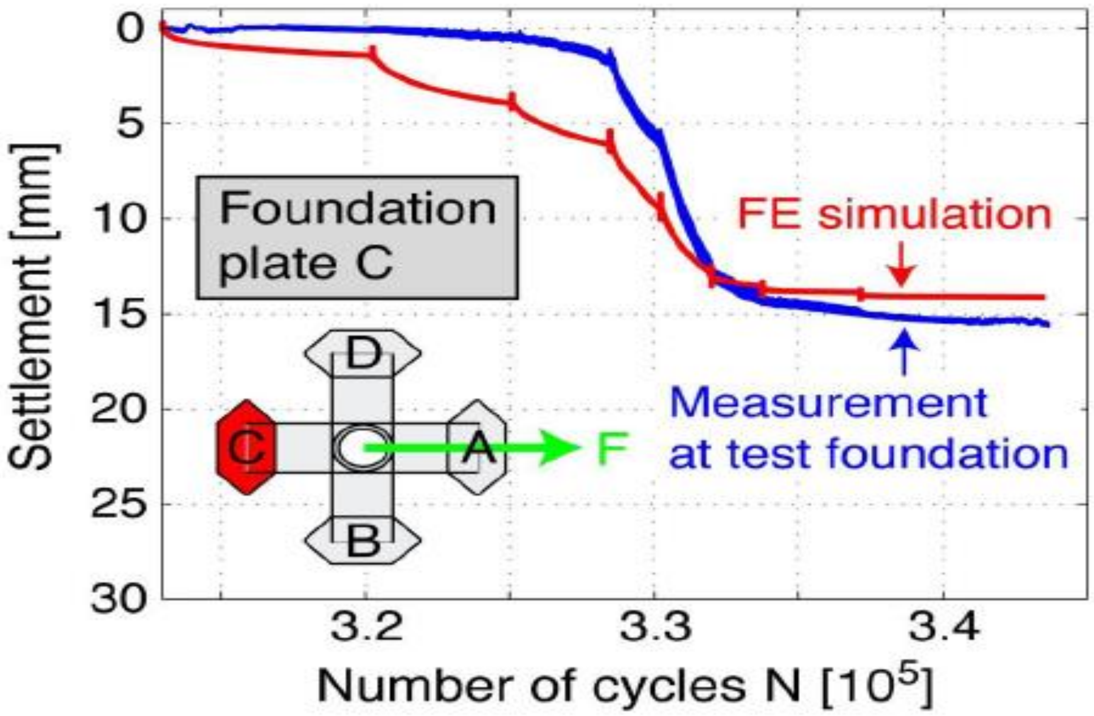


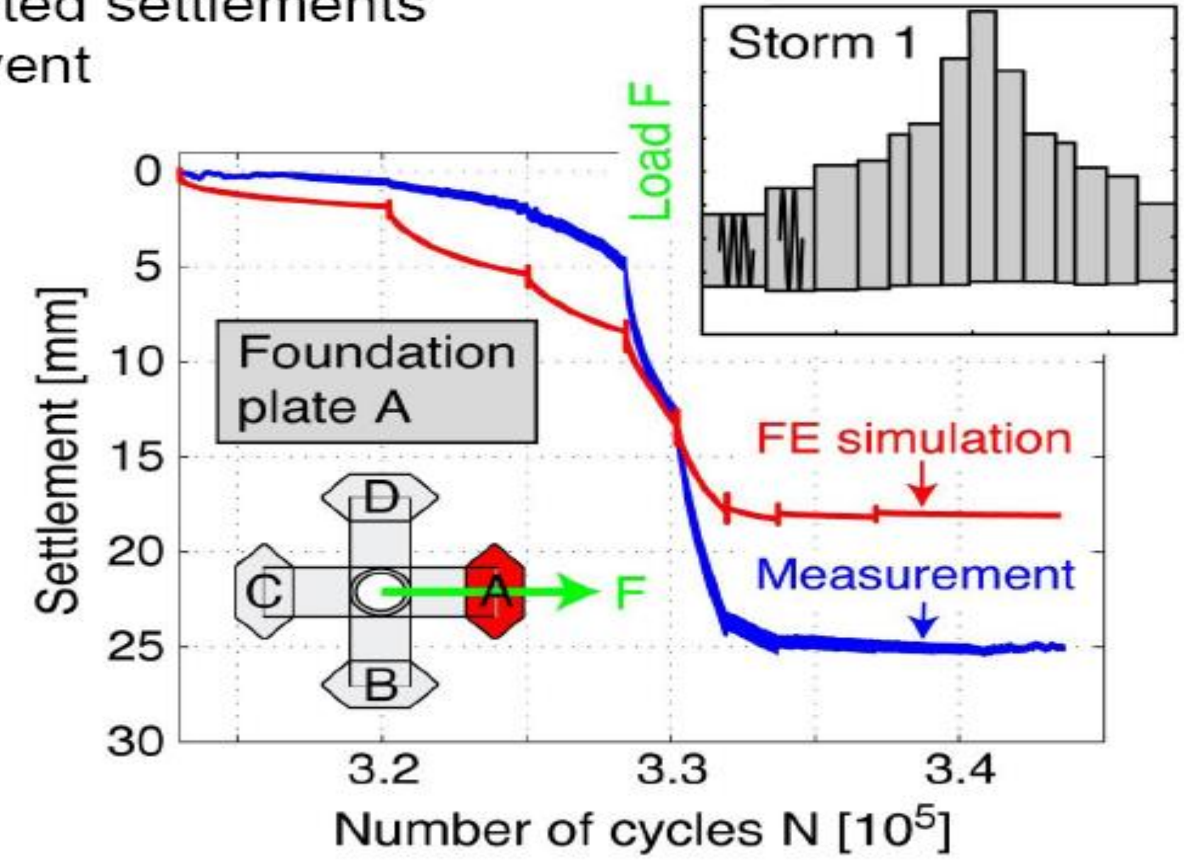


Zachert et al. (2020)

- FE-model (87000 brick elements)
- Determination of HCA model parameters at the istitute of soil
- mechanics and rock mechanics IBF(KIT)

- Comparison of measured and calculated settlements of plates A and C during first storm event



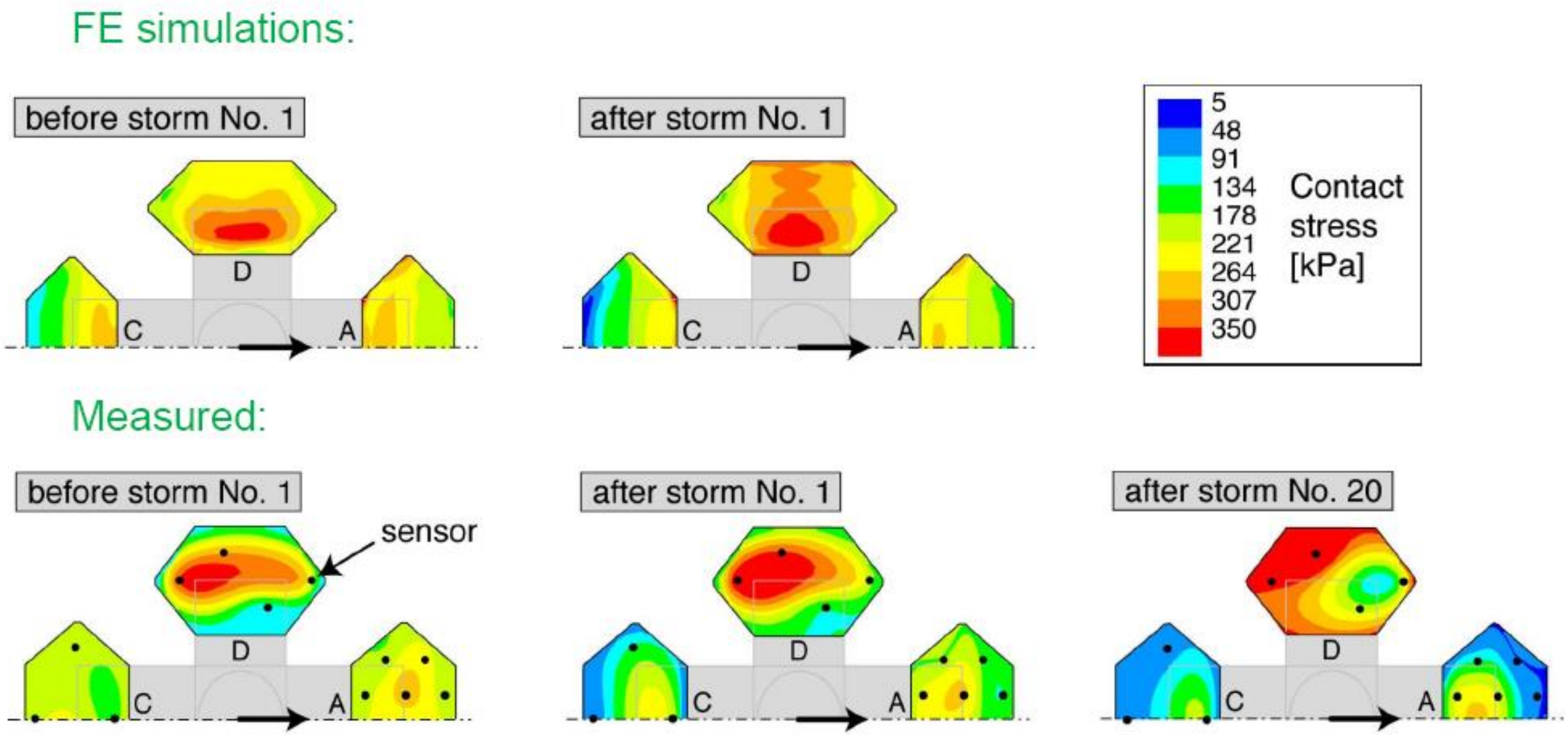


→ Satisfying agreement between measured data and FE simulations for plate C, underestimation of settlement for plate A

Zachert et al. (2020)

Validations of the HCA Model with model and in situ tests

- Contact stresses: Redistribution from plates A and C to B and D



→ Qualitative and quantitative similar

Zachert et al. (2020)

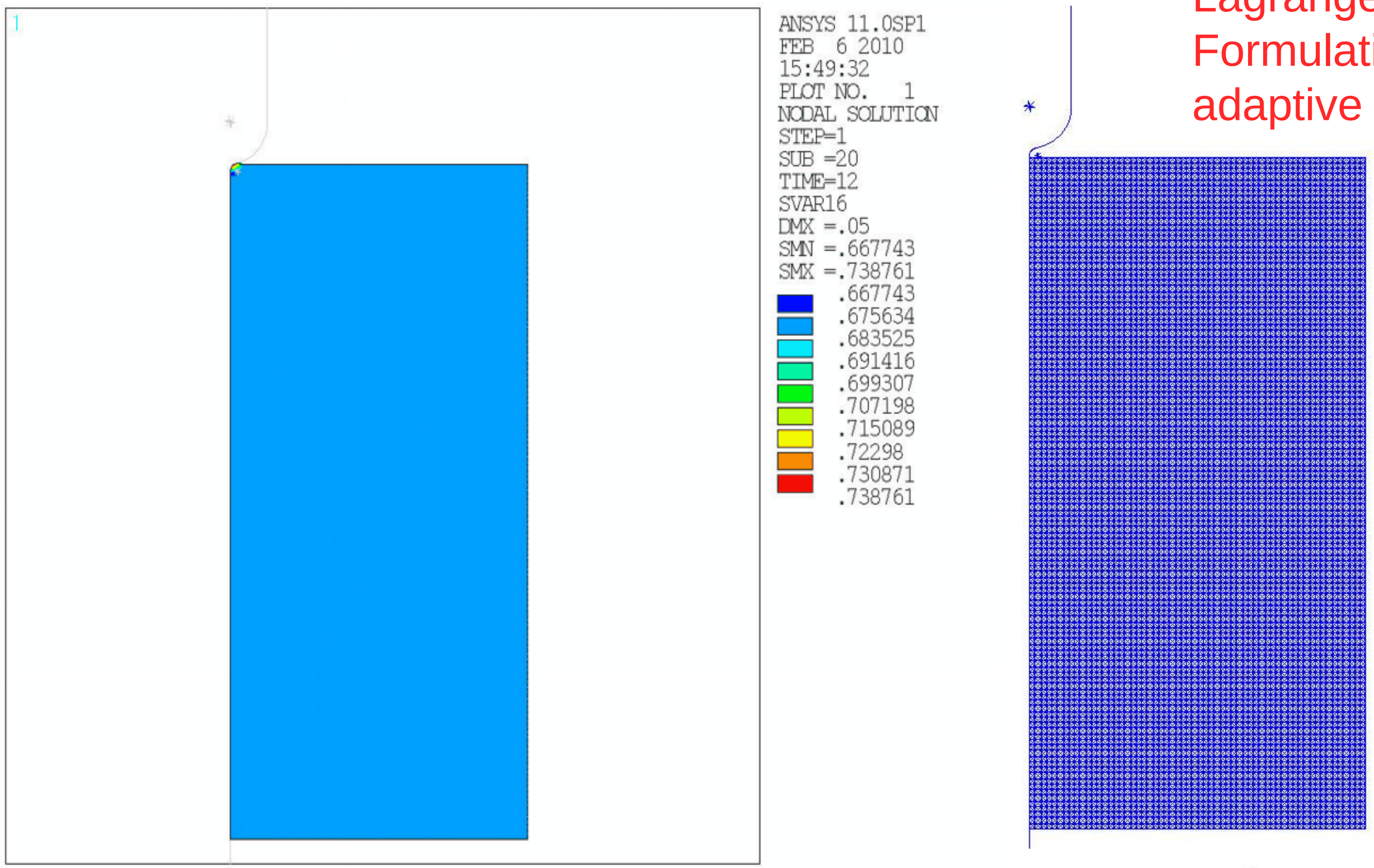
Before the first storm event the model predict an increasing concentration of stresses perpendicular to the direction of loading and this effect seems to become more pronounced with the number of the storm events.

Similar results have been also measured in the in situ test validating the model's predictions

Influence of the installation methods on behaviour of monopile foundation

Quasi-static pile penetration in dry sand:

Evolution of void ratio



Calculations with a combined Euler – Lagrange Formulation and adaptive FE meshing

$$\dot{\phi} = \frac{\partial \hat{\phi}}{\partial t} + \nabla_c \phi$$

Material time derivative

Local time derivative at fixed reference point

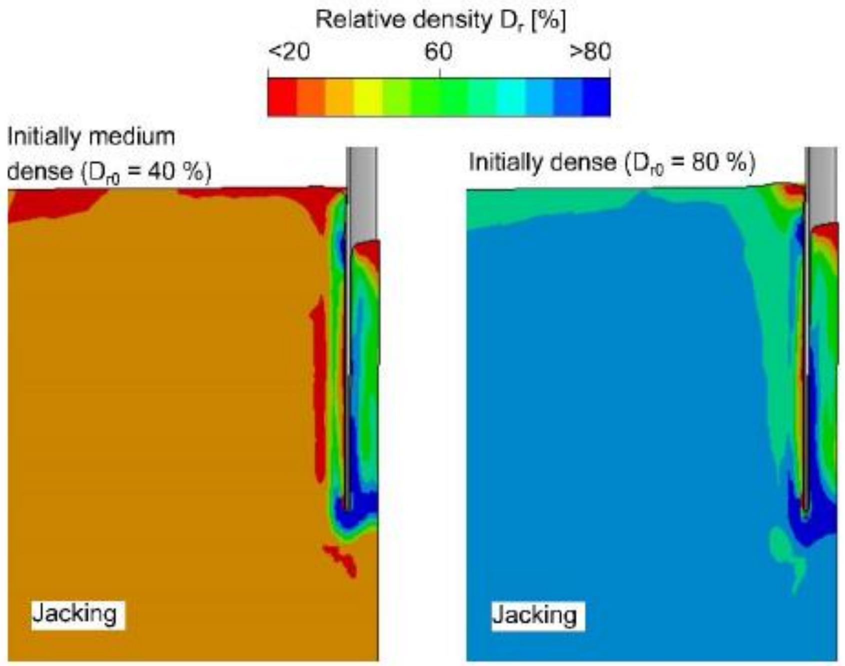
Convective term due to relative velocity

$c = 0$	**Lagrange**
$c = v$	**Euler**

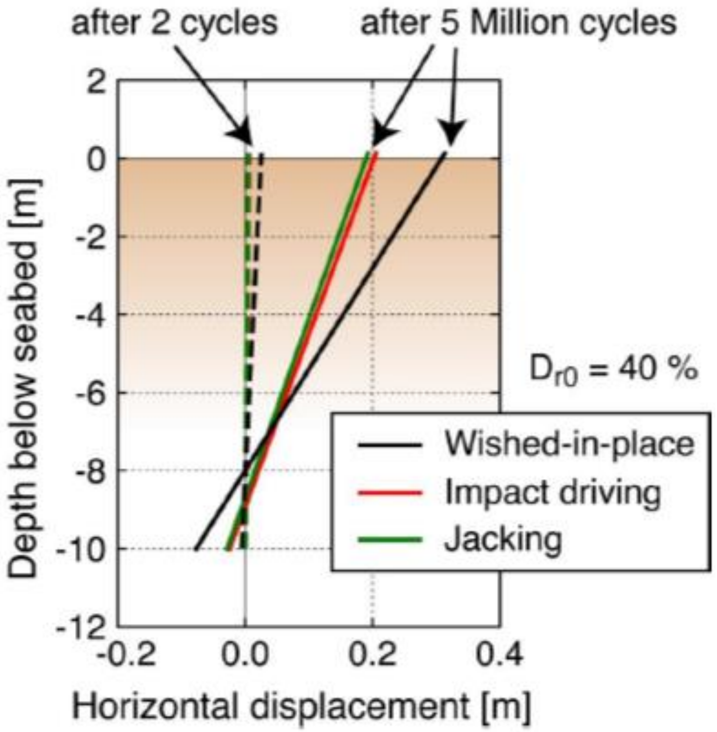
Aubram et al., : Numerical and experimental investigation on vibro-injection piles installation, 2012, 2nd WS, FOR 1136 Geotech, Technical Univ. of Berlin

Influence of the installation methods on the high cycle behaviour of WT monopile foundation

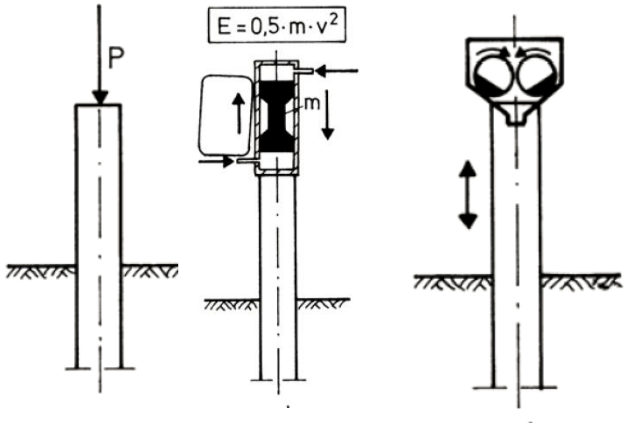
Density changes due to installation (simulated with a CEL model, afterwards state is transfered to Langrangian model)



Pile deflections due to high-cyclic loading:



Further installation methods:
- Impact driving
- Vibratory driving
- Boring
- and combinations thereof

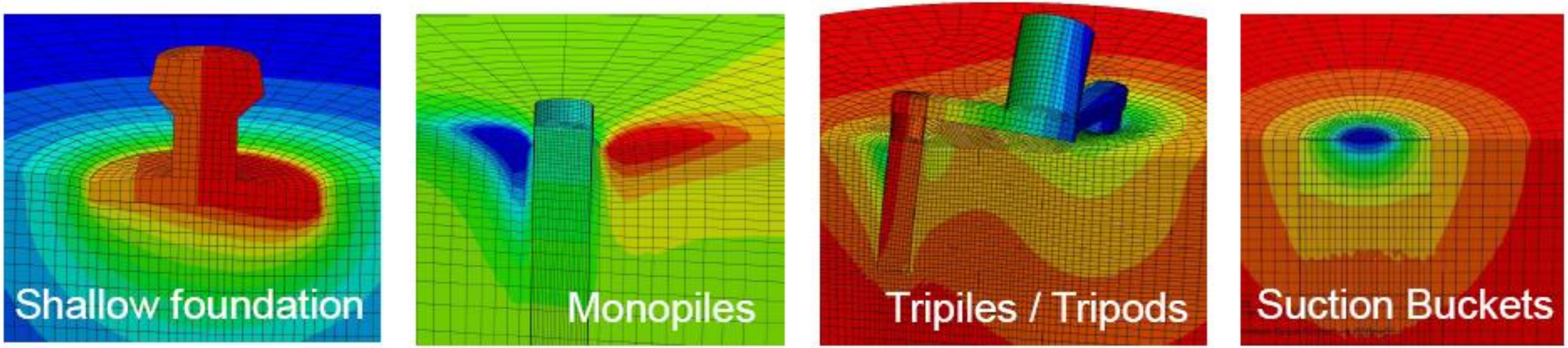


Jacking   Impact driving   Vibratory driving

Staubach, P., Machacek, J., Moscoso, M.C., Wichtmann, T. (2020): *Impact of different installation procedures on the long-term cyclic behaviour of piles in sand: a numerical study.* Soil Dynamics and Earthquake Engineering, Vol. 138, Paper No. 106223

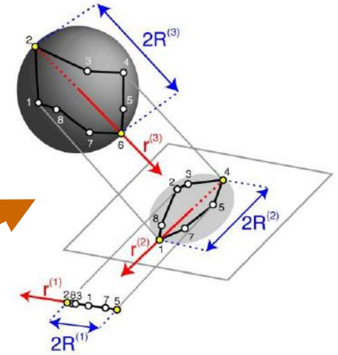
Summary

- **The high cycle loading on the foundation structure due to wind and waves can be easely captured by the HCA Modell**
- **HCA model requires:**
  - **Cyclic triaxial tests**
  - **Detailed determination of material parameters and soil parameters**
- **HCA model is validated with small scale model tests and real scale tests (settlements, PWP development and contact pressure rearrangement)**
  - **Flexible in application to conventional or new types of foundation structure or to any boundary value problem without restrictions**



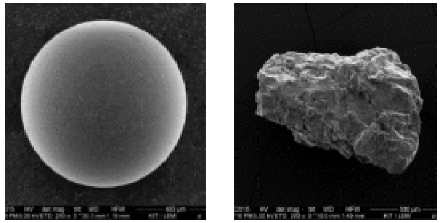
Summary

•The accumulated strain increases with increasing strain amplitude, decreasing density and increasing average stress ratio

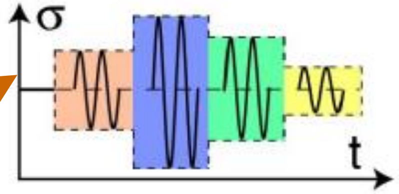


•The definition of the multidimensional amplitude has been confirmed with up to 4-D cyclic strain paths

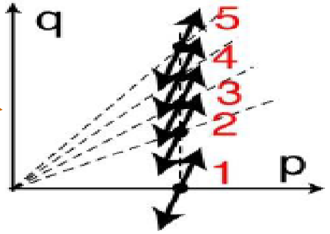
•The accumulated strain increases with decreasing mean grain size d_{50} and increasing uniformity coefficient C_u



•The shape and the surface characteristics of the grains have a strong influence on the amplitude and pressure dependence of the strain accumulation



•The bundling of a cycling loading with random amplitudes into series of packages with constant amplitude is conservative. The accumulation of different amplitudes can be dealt with fractional calculus



•Monotonic loading phases between packages of cycles may partly erase the cyclic preloading memory – ongoing research

•Installation methods influence strongly the cyclic behaviour of monopiles and they have to be considered – ongoing research

Thank you for your attention!