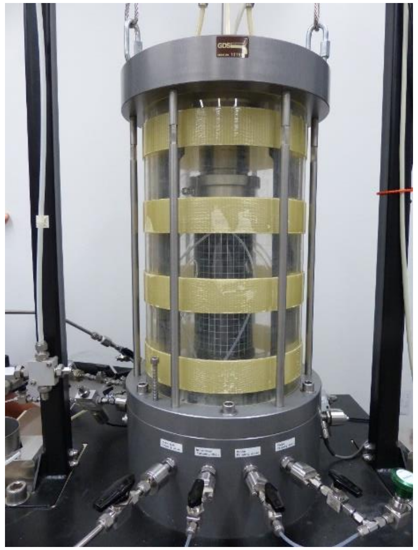
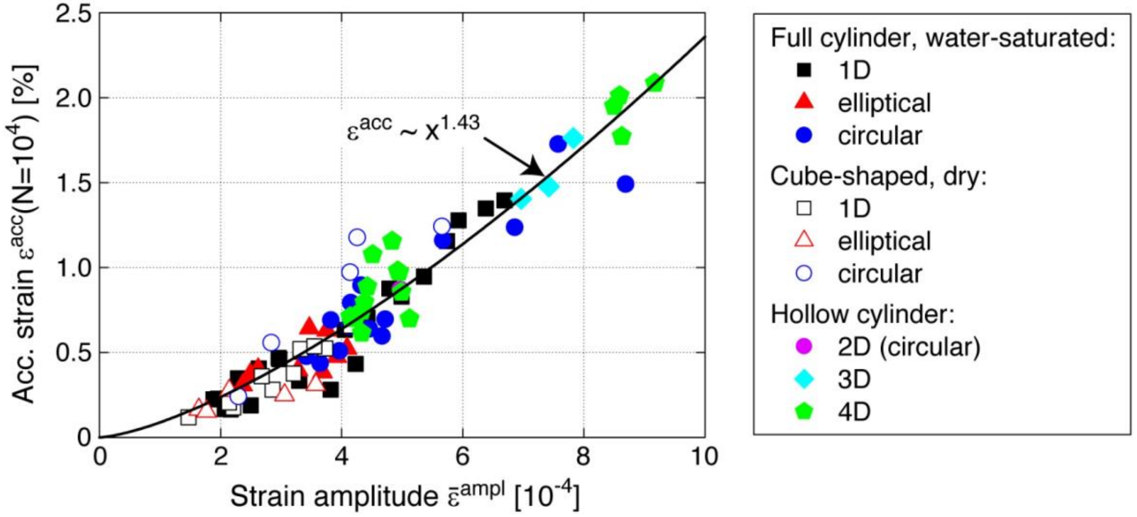
Numerical calculations of an offshore wind turbine based on high-cyclic triaxial tests

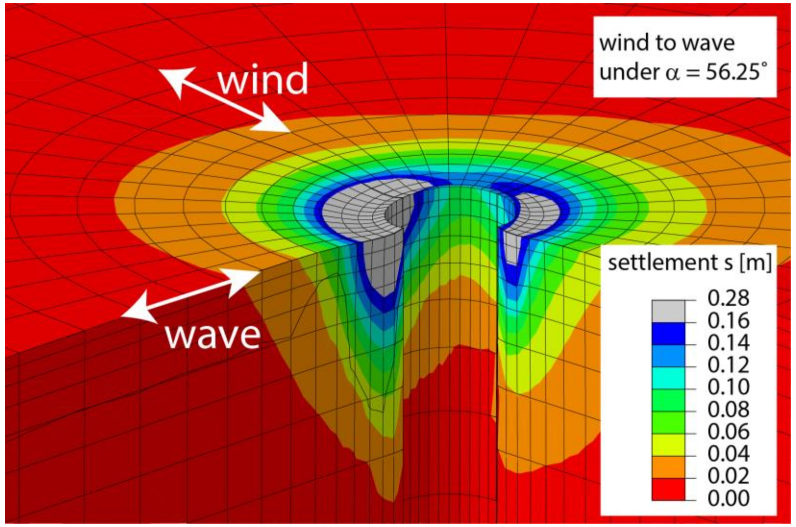
Dr.-Ing. Lukas Knittel

Institute of Soil Mechanics and Rock Mechanics (IBF), Karlsruhe Institute of Technology (KIT)

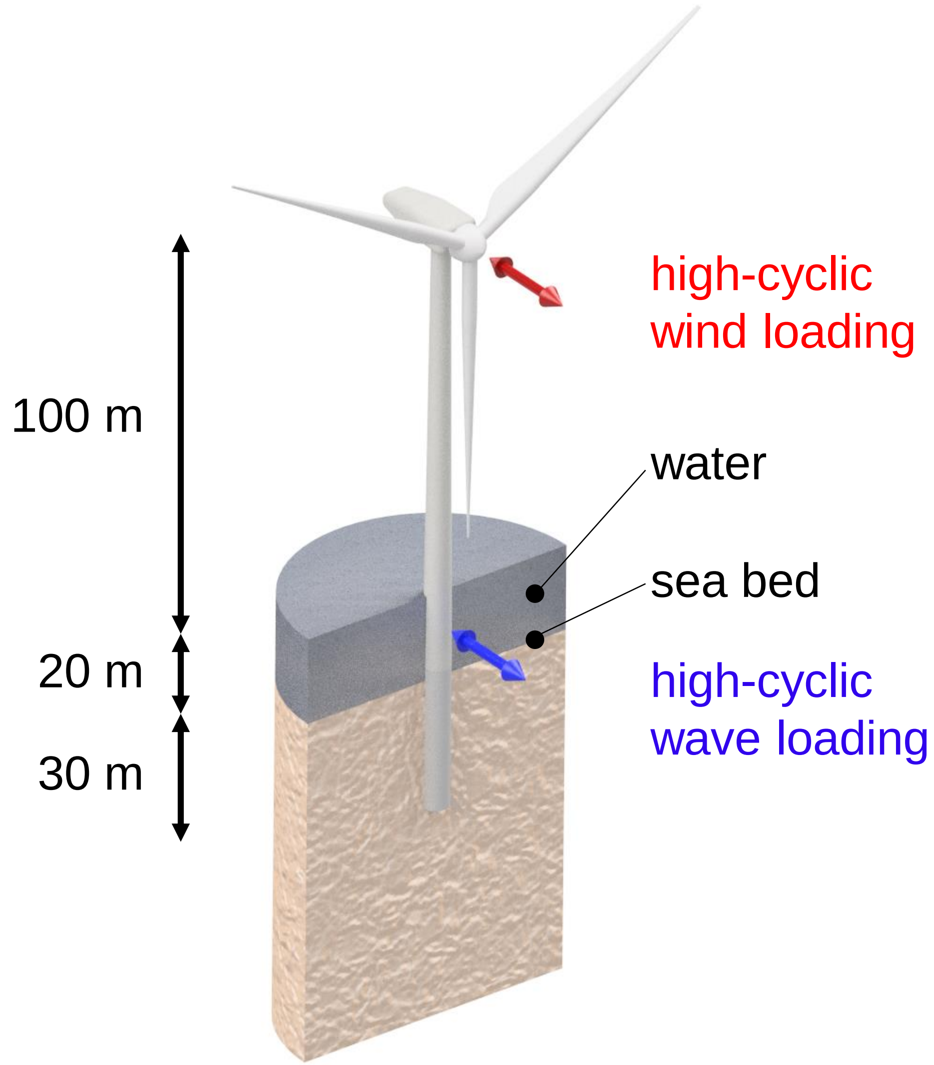
Mail: lukas.knittel@kit.edu, Phone: +49 721 608 45158







Content



high-cyclic
wind loading
100 m
water
sea bed
20 m
high-cyclic
wave loading
30 m

Practical question

Foundation of an offshore wind turbine (OWT)

Combined high cyclic wind- and wave loads with different:

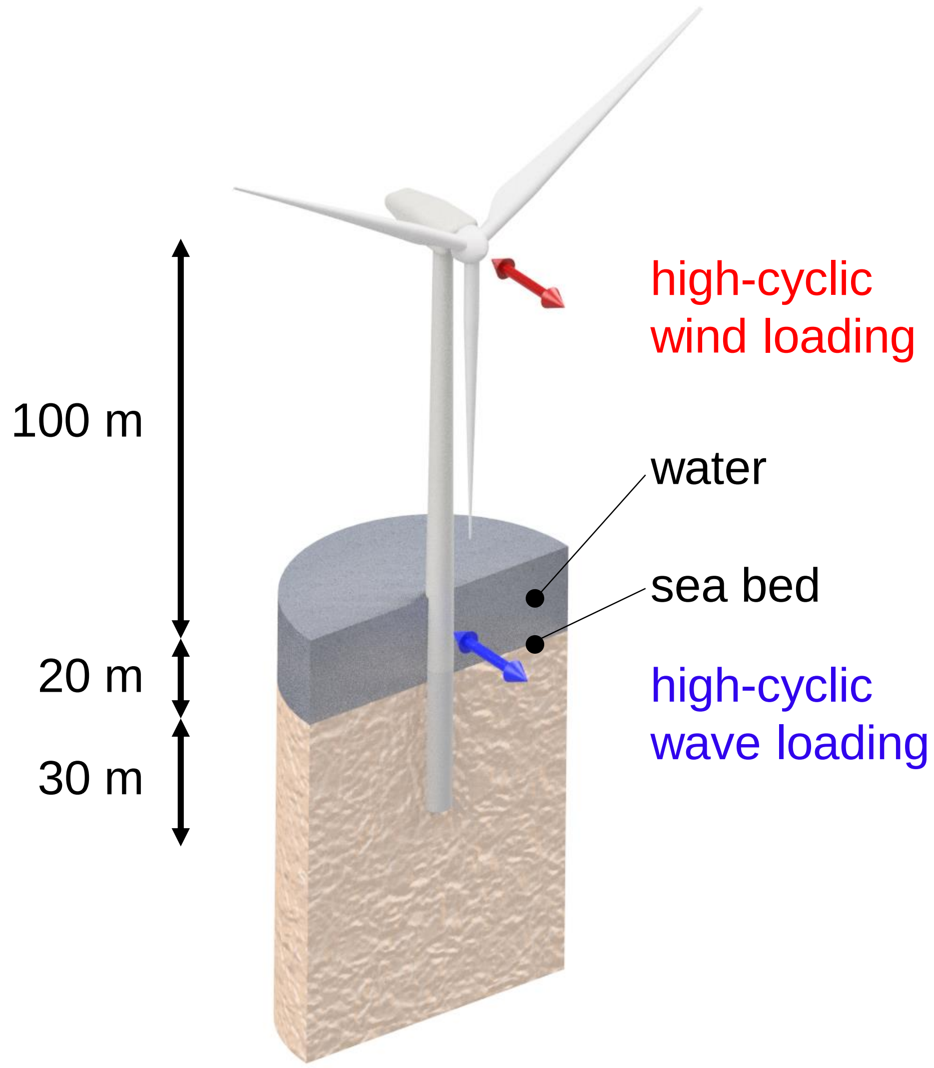
- Direction ($\alpha \leq 60°$)
- Frequency
- Amplitude

Multidimensional cyclic loading:

- Variation of different components of the stress or strain tensor
- Orientation of the stress path

Loss of serviceability ($\theta \leq 0{,}5°$)

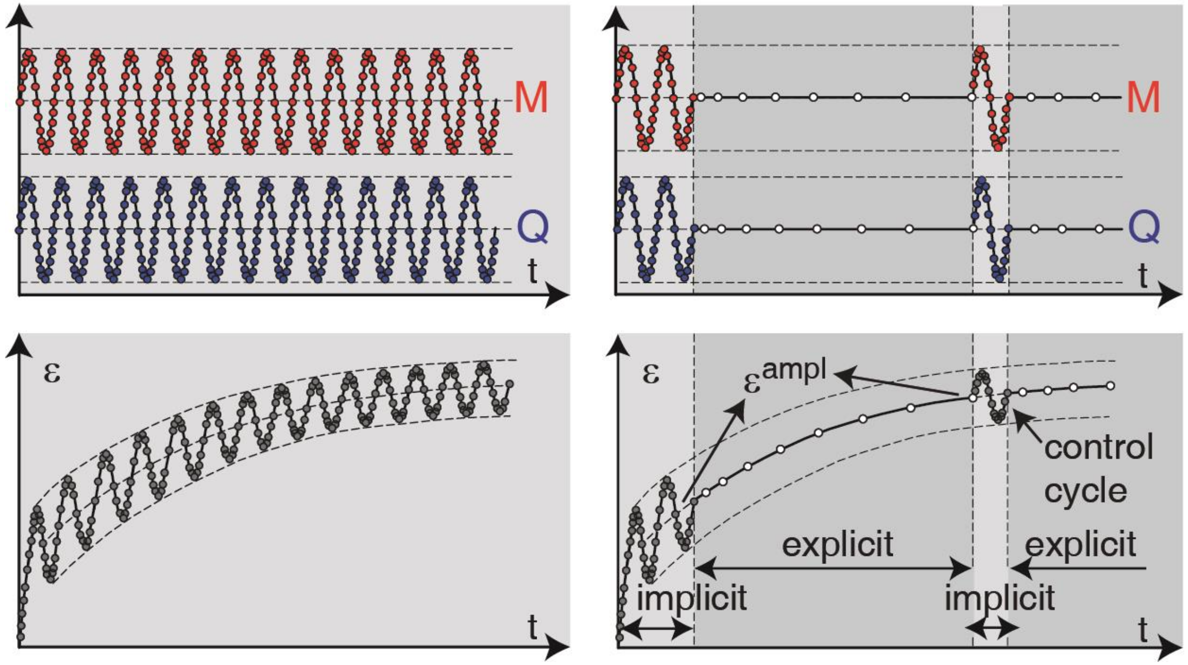
Aim: Investigation of the behavior of granular soils under multidimensional cyclic loading.



Numerical calculations

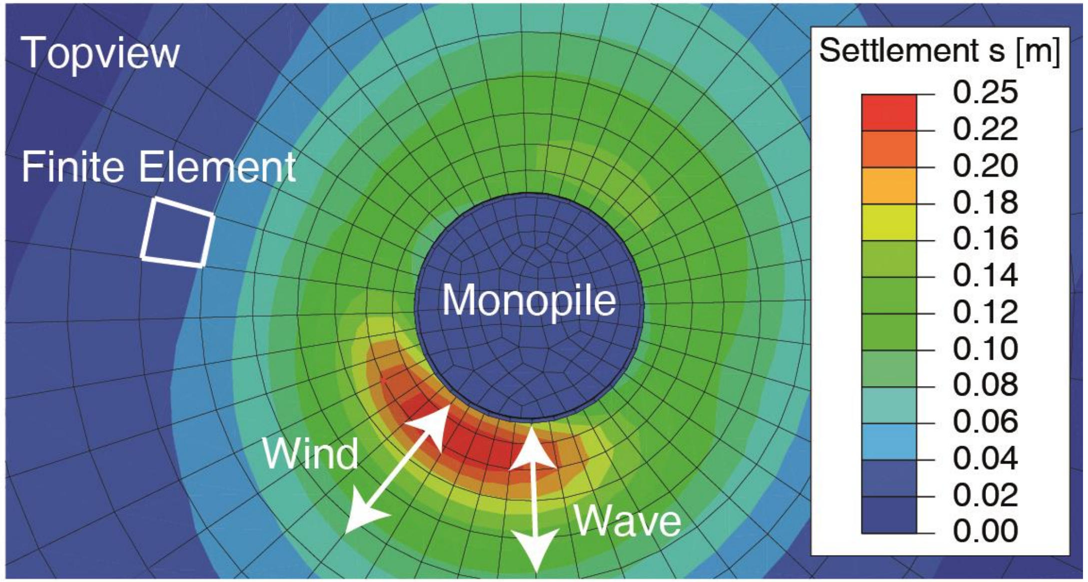
a) pure "implicit" calculation

b) mixed "implicit" and "explicit" calculation



Monopile under cyclic wind and wave loads:

Resulting shear force Q or bending moment M

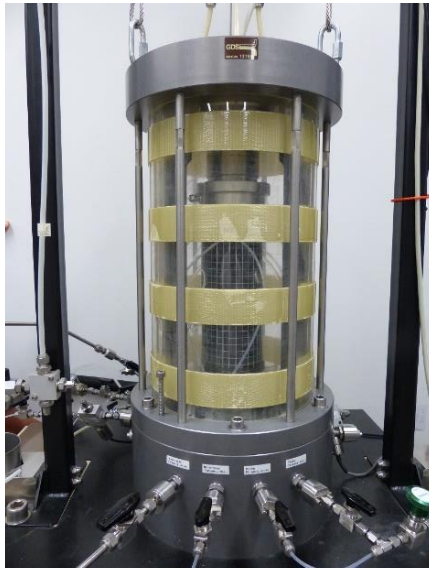


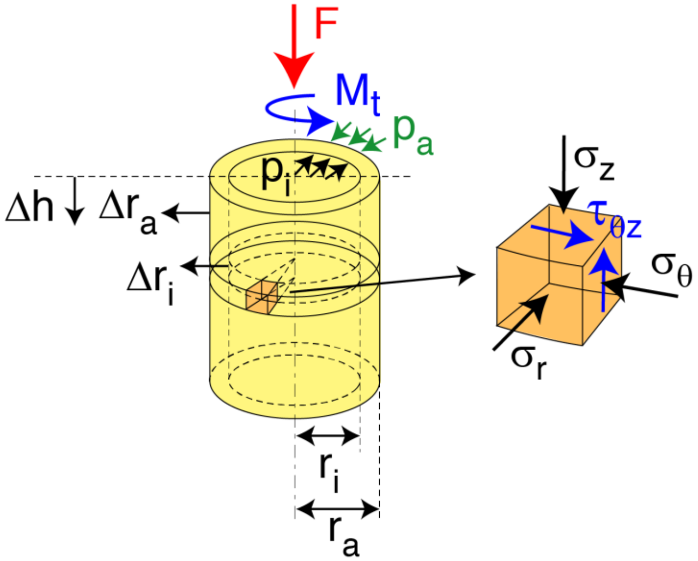
a) Applicability limited to only a few cycles (N < 50) as well as large computational effort.

b) Explicit models: description of the trend of strain, especially for highly cyclic processes.
Change of ε^{ampl} due to stress rearrangement or compression → control cycle.

Implicit constitutive models

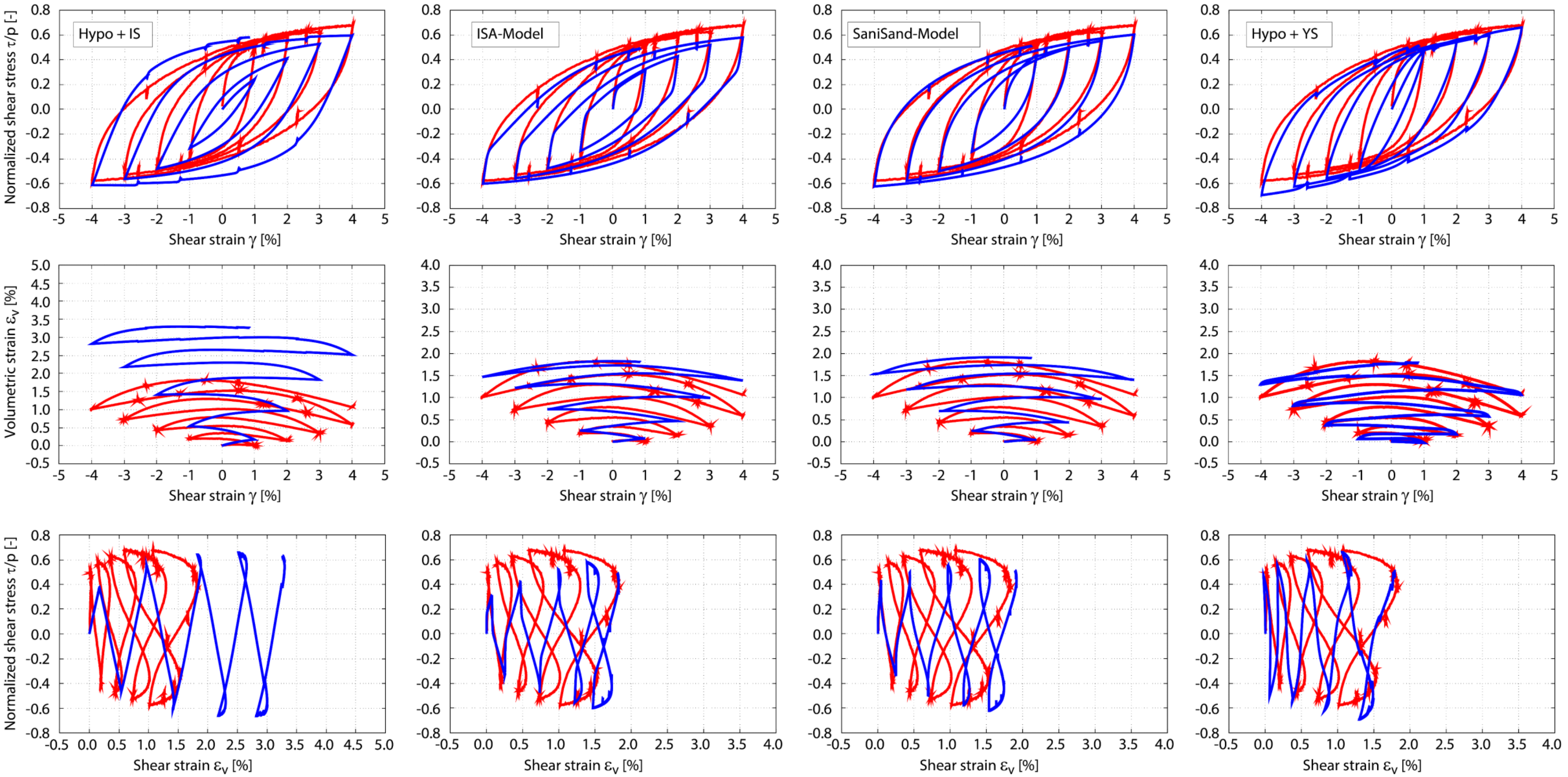
No.	Constitutive Model	Developer	Year	implemented
1	Hypoplasticity with Intergranular Strain	Niemunis and Herle	1997	Niemunis
2	Simple Anisotropic Sand Plasticity Model	Taiebat and Dafalias	2007	Tafili
3	Intergranular Strain Anisotropy Model	Fuentes	2014	Tafili
4	Hypoplasticity with a Historiotropic Yield Surface	Grandas et al.	2020	Grandas





- Isotropic average stresses: p^{av} = 200 kPa
- Cyclic regulation of the torsion angle θ for particular shear strains γ
- Karlsruhe fine sand: $d_{50} = 0.14$ mm, $C_u = \frac{d_{60}}{d_{10}} = 1.5$

Implicit constitutive models



Schwarzweller, Tafili & Knittel, IBF, KIT (2019)

Implicit constitutive models

No.	Constitutive Model	Developer	Year
1	Hypoplasticity with Intergranular Strain	Niemunis and Herle	1997
2	Simple Anisotropic Sand Plasticity Model	Taiebat and Dafalias	2007
3	Intergranular Strain Anisotropy Model	Fuentes	2014
4	Hypoplasticity with a Historiotropic Yield Surface	Grandas et al.	2020

used in numerical calculations

best reproduction of test results

Hypoplasticity with Intergranular Strain:

$\boxed{\dot{\boldsymbol{\sigma}} = \mathrm{M}(\boldsymbol{\sigma}, \boldsymbol{h}, e, \dot{\boldsymbol{\varepsilon}}) : \dot{\boldsymbol{\varepsilon}}}$ with stress rate $\dot{\boldsymbol{\sigma}}$, stiffness M, effective stress $\boldsymbol{\sigma}$, intergranular strain $\boldsymbol{h}$, void ratio e and deformation rate $\dot{\boldsymbol{\varepsilon}}$.

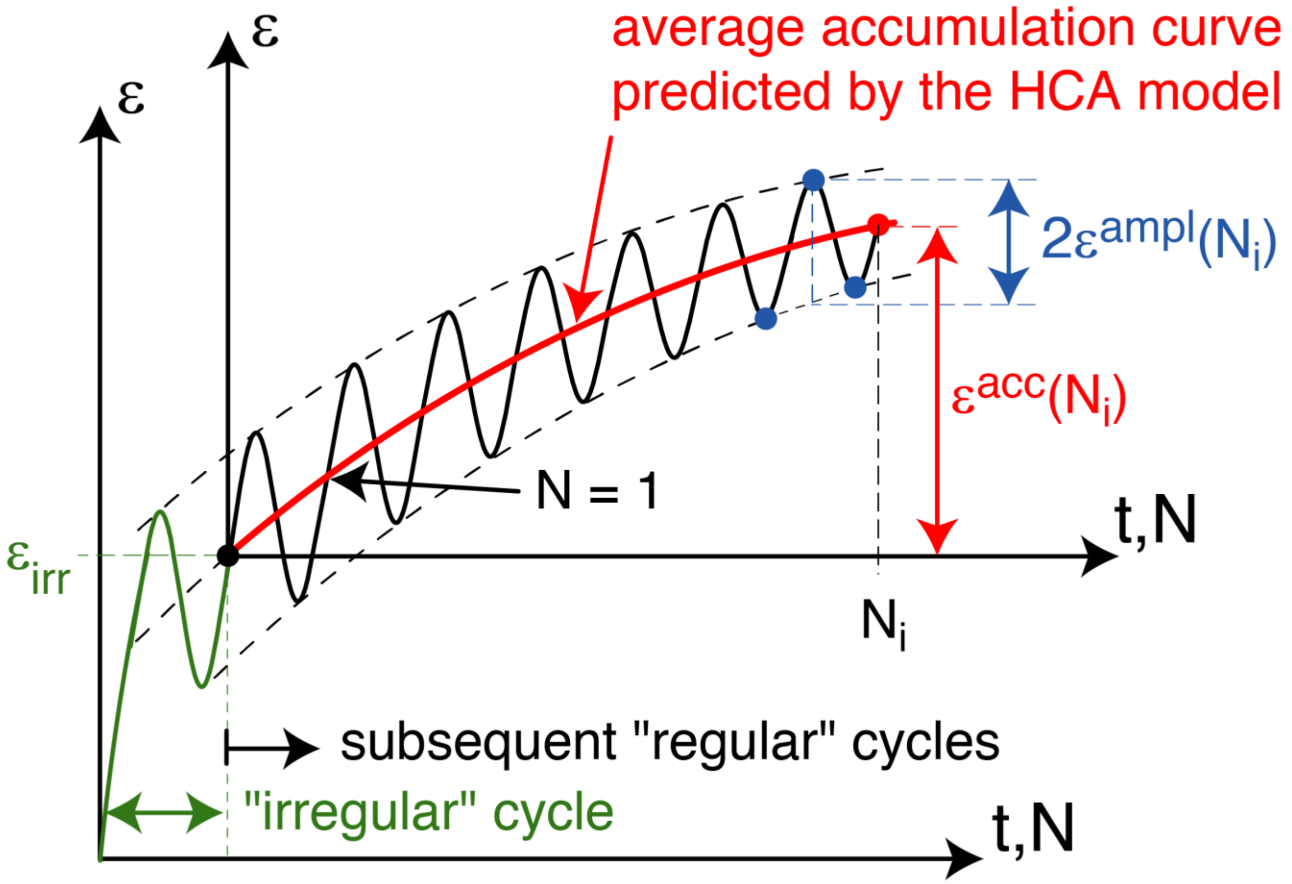
Calibration of 13 parameters of the constitutive model from test results:

Hypoplasticity φ_c, h_s, n, α, β, e_{i0}, e_{c0}, e_{d0} and intergranular strain m_R, m_T, R, β_r, χ.

High-cycle accumulation (HCA) model (Niemunis et al. 2005)

Scope HCA-model:

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



High-cycle accumulation (HCA) model (Niemunis et al. 2005)

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

$\dot{\boldsymbol{\sigma}}$ = 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)

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

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

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

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
f_π = Changes of polarization

$$f_{\mathrm{ampl}} = \left(\frac{\varepsilon^{\mathrm{ampl}}}{10^{-4}}\right)^{C_{ampl}}$$

Definition of the strain amplitude $\varepsilon^{\text{ampl}}$ in the HCA model

- General definition of a (6D-strain-space) strain amplitude tensor and one loading cycle:

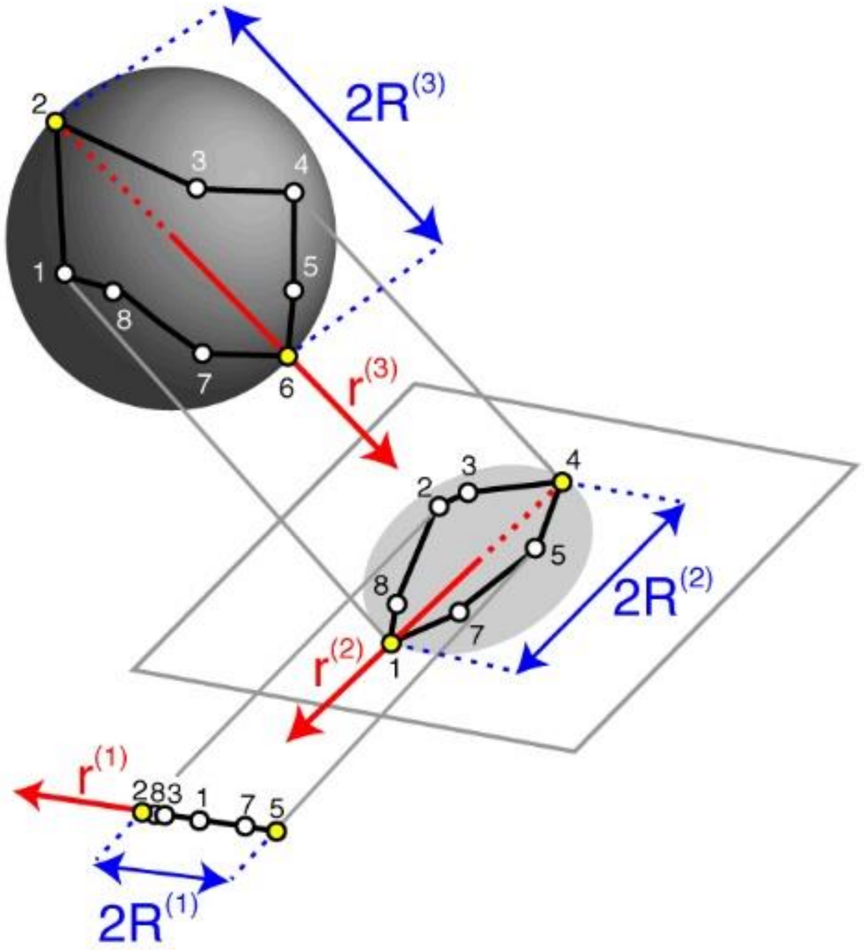
$$\boxed{\varepsilon^{\text{ampl}} = \|\mathbf{A}_\varepsilon\|}$$

$$\boxed{\mathbf{A}_\varepsilon = \sum_{i=1}^{6} R^{(i)}\, \vec{\mathbf{r}}^{(i)} \otimes \vec{\mathbf{r}}^{(i)}}$$

- Strain amplitude $\varepsilon^{\text{ampl}}$ is obtained from spans $2R^{(i)}$ and directions $\vec{\mathbf{r}}^{(i)}$ determined from a series of projections of the strain loop from the 6D to 1D space

$$\boxed{\varepsilon^{\text{ampl}} = \sqrt{(R^{(3)})^2 + (R^{(2)})^2 + (R^{(1)})^2}}$$

- Confirmed for 1D and 2D strain paths (Wichtmann et al.)
- Purpose: Validation for up to 4D paths



Testing program

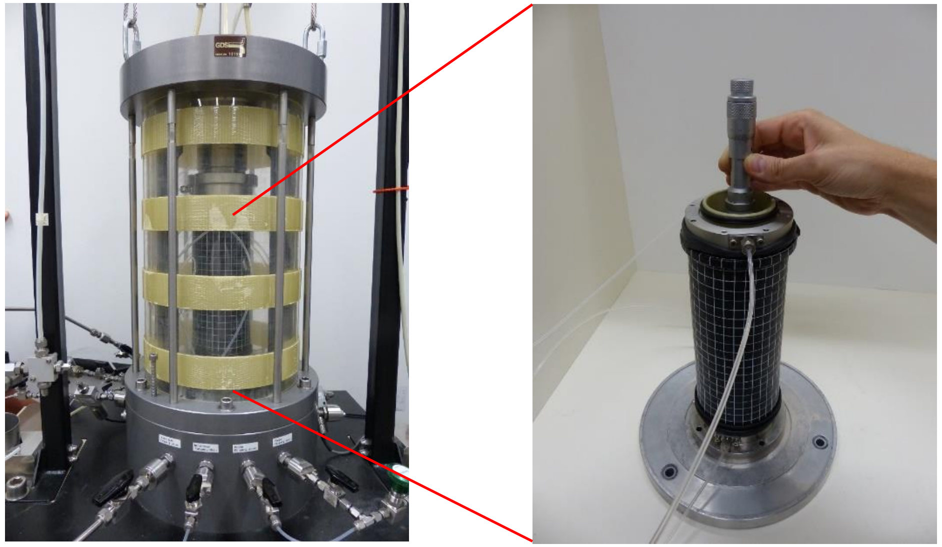
- Karlsruhe fine sand: $d_{50} = 0.14$ mm, $C_u = \frac{d_{60}}{d_{10}} = 1.5$, $I_{D0} \approx 0.40$ or 0.70 ($\mathrm{D_{r0}} \approx 40\%$ or 70%)

Drained 1D- and 2D-stress paths

$h = 200$ mm, $d = 100$ mm
$h = d = 100$ mm

180 x 90 x 90 mm
LDT´s

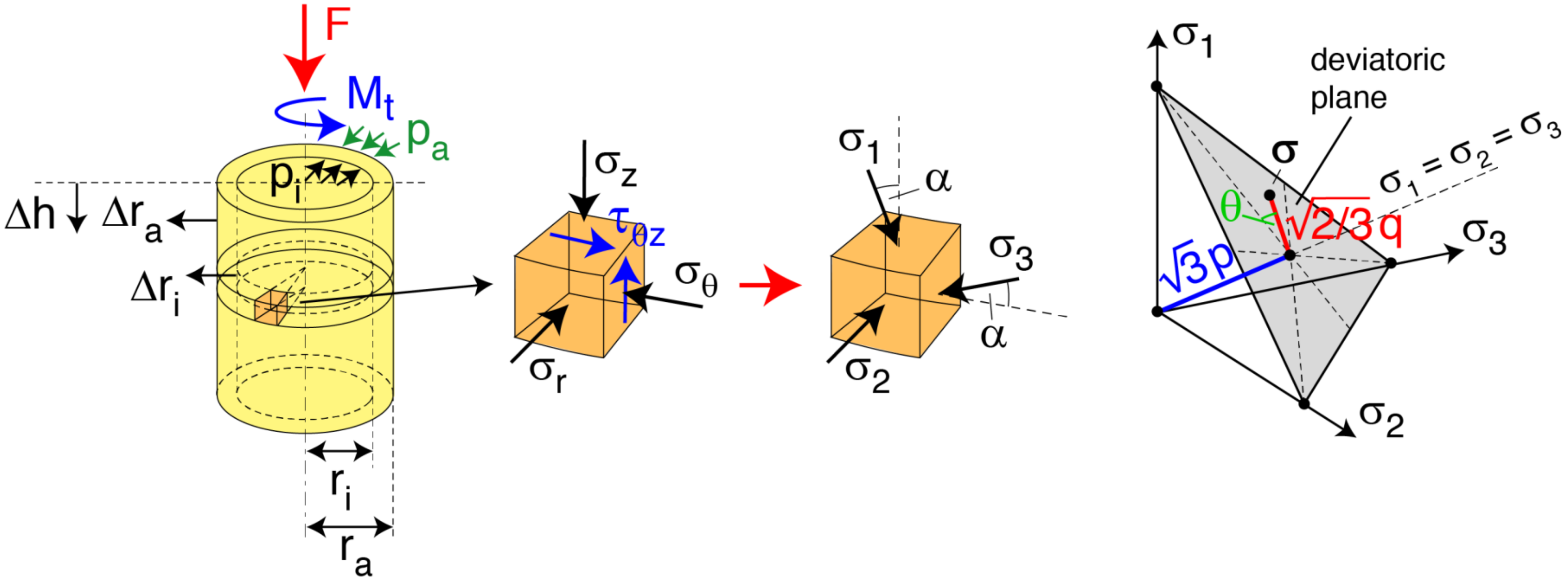
Drained 2D- to 4D-stress paths



$h = 200$ mm, $d_a = 100$ mm, $d_i = 60$ mm

- Average stress state: $p^{\mathrm{av}} = 200$ kPa, $\eta^{\mathrm{av}} = 0.50$
- 120 cyclic triaxial tests (each N = 10,000 with test duration ≈ 1 week)
- Evaluation with Python- and Fortran scripts

Hollow cylinder testing device (1D- to 4D-stress paths)



Control parameters:

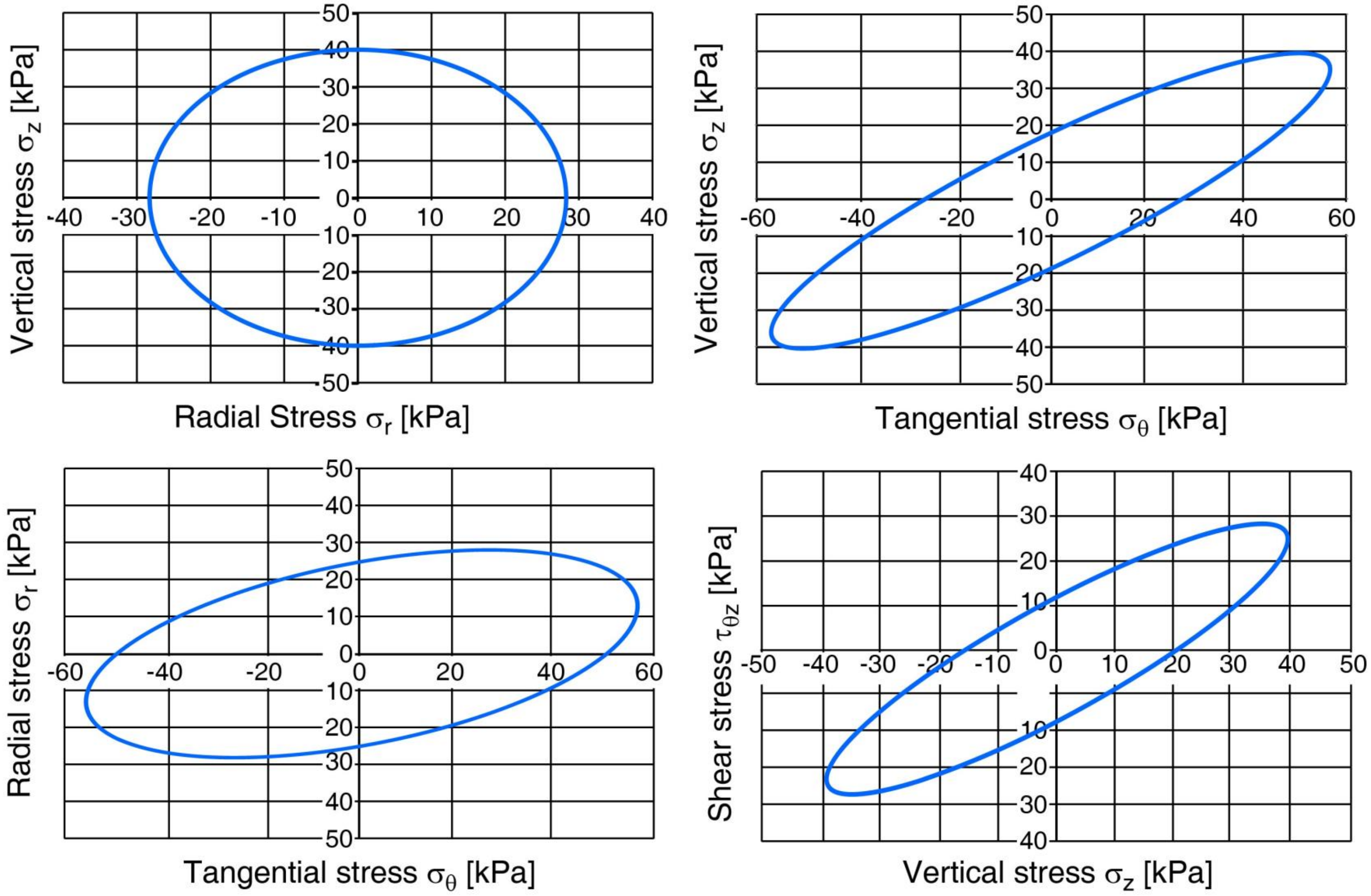
- Vertical force F
- Outer pressure p_a
- Inner pressure p_i
- Torque M_T

Stress tensor with 4 independent components (= „4D“):

$$\sigma = \begin{pmatrix} \sigma_z & \tau_{\theta z} & 0 \\ \tau_{\theta z} & \sigma_\theta & 0 \\ 0 & 0 & \sigma_r \end{pmatrix}$$

„1D“- to „4D“-
stress paths possible

Hollow cylinder testing device (2D-, 3D-, 4D-stress paths)



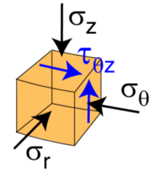
Average value of stress [kPa]			
σ_z^{av}	σ_r^{av}	σ_θ^{av}	$\tau_{\theta z}^{av}$
266.67	166.67	166.67	0.00

const.

Dimen-sion (D)	Stress amplitude [kPa]			
	σ_z^{ampl}	σ_r^{ampl}	σ_θ^{ampl}	$\tau_{\theta z}^{ampl}$
2D	40.00	28.28	28.28	0.00
3D			56.56	0.00
4D			56.56	28.28

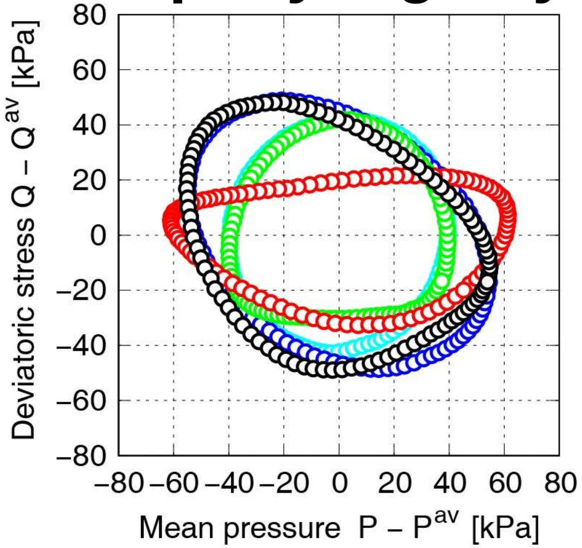
const.

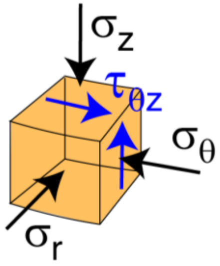
$$\sigma = \begin{pmatrix} \sigma_z^{av} + \sigma_z^{ampl} & \tau_{z\theta}^{av} + \tau_{z\theta}^{ampl} & 0 \\ \tau_{z\theta}^{av} + \tau_{z\theta}^{ampl} & \sigma_\theta^{av} + \sigma_\theta^{ampl} & 0 \\ 0 & 0 & \sigma_r^{av} + \sigma_r^{ampl} \end{pmatrix}$$



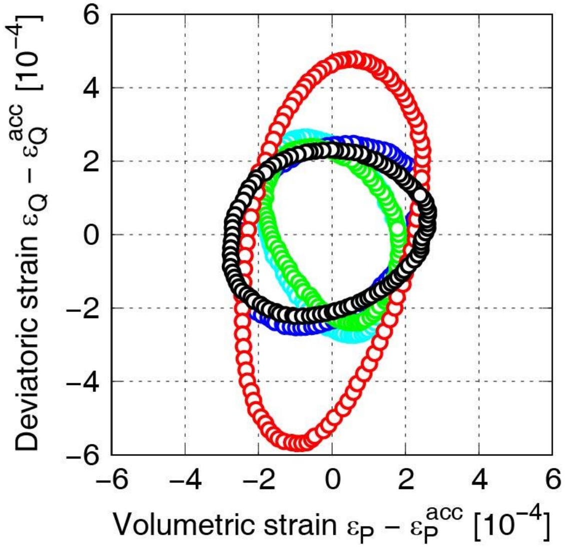
$$\sigma = \begin{pmatrix} \sigma_z & \tau_{\theta z} & 0 \\ \tau_{\theta z} & \sigma_\theta & 0 \\ 0 & 0 & \sigma_r \end{pmatrix}$$

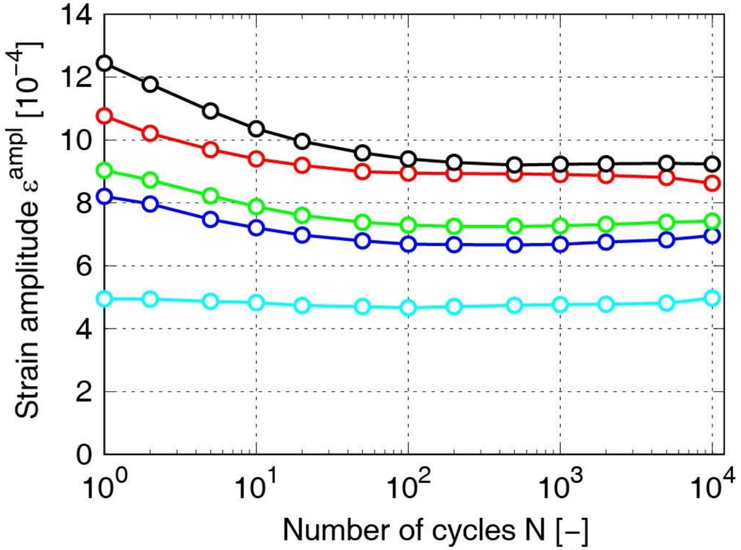
Exemplary high-cyclic hollow cylinder triaxial tests

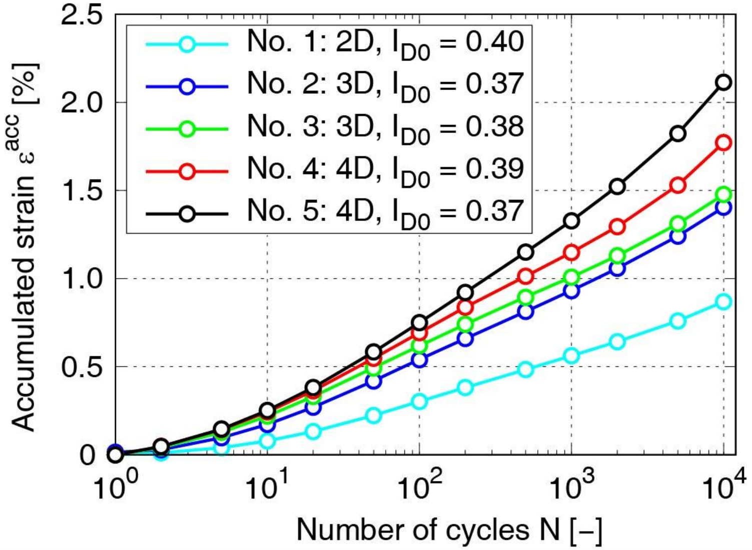




	Average value of stress [kPa]				Stress amplitude [kPa]				Phase-shift [°]			
No.	σ_z^{av}	σ_r^{av}	σ_θ^{av}	$\tau_{\theta z}^{av}$	σ_z^{ampl}	σ_r^{ampl}	σ_θ^{ampl}	$\tau_{\theta z}^{ampl}$	φ_{σ_z}	φ_{σ_r}	φ_{σ_θ}	$\varphi_{\tau_{\theta z}}$
1							28.28	0.00				
3	266.67	166.67	166.67	0.00	40.00	28.28	28.28	28.28	35.26	125.26	125.26	**125.26**
5							56.56	**28.28**				

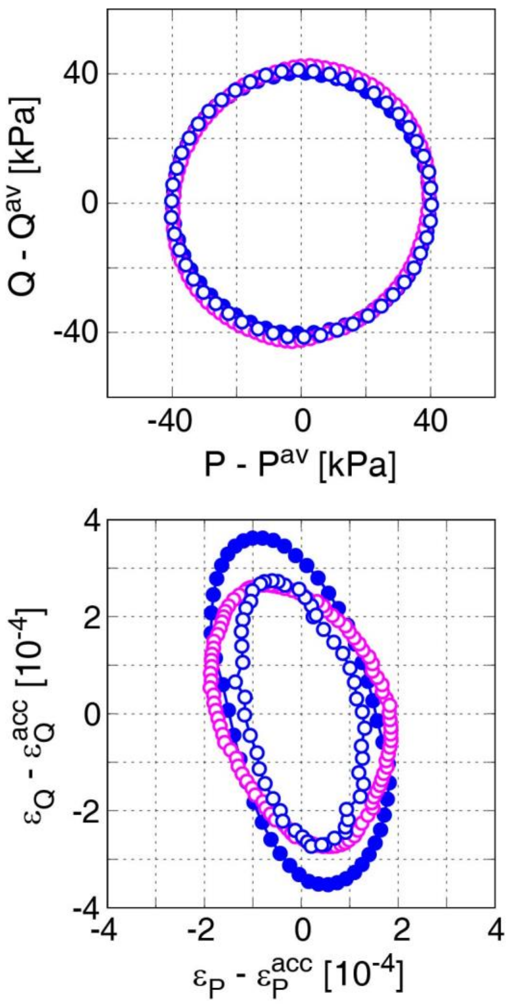




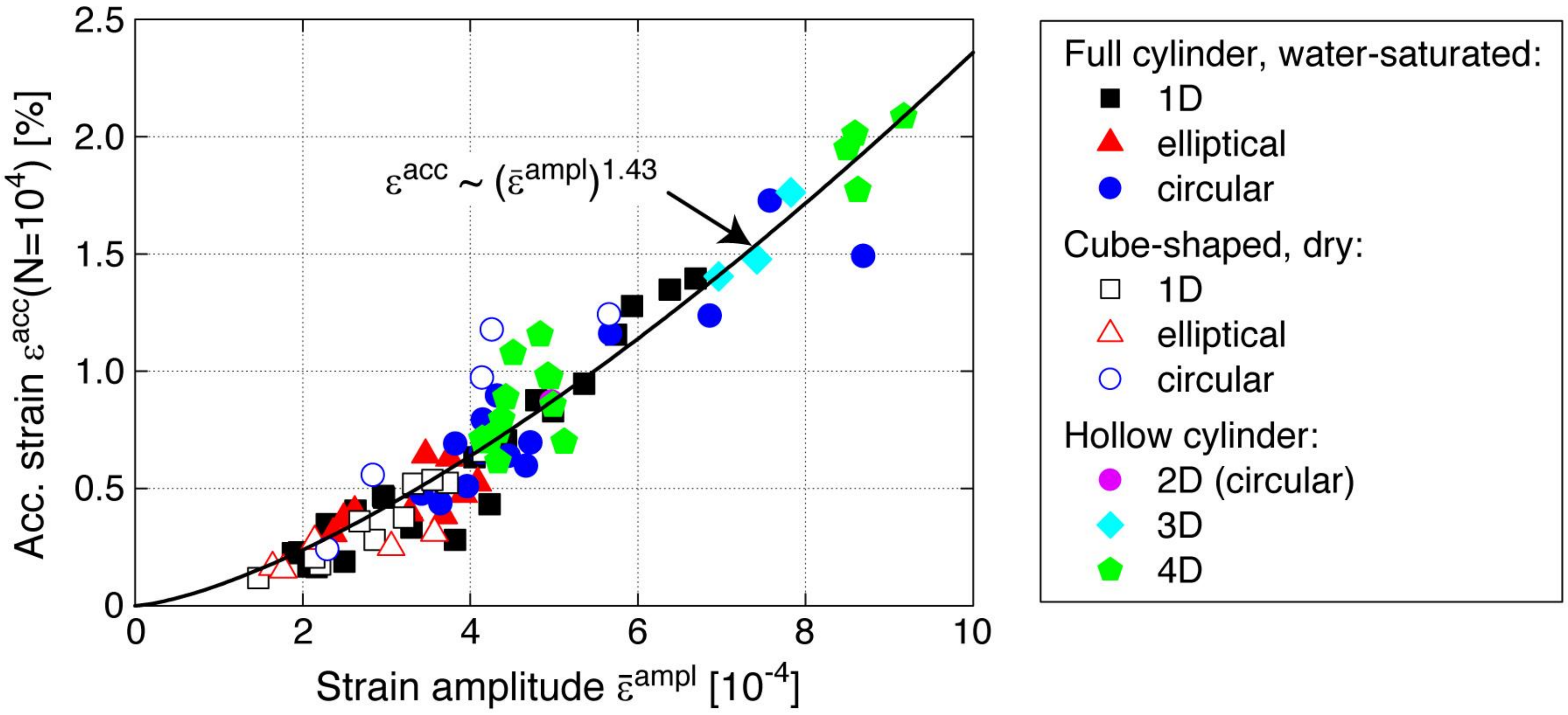


Results of high-cyclic triaxial tests

2D (circular)



KFS (I_{D0} = 0.40)



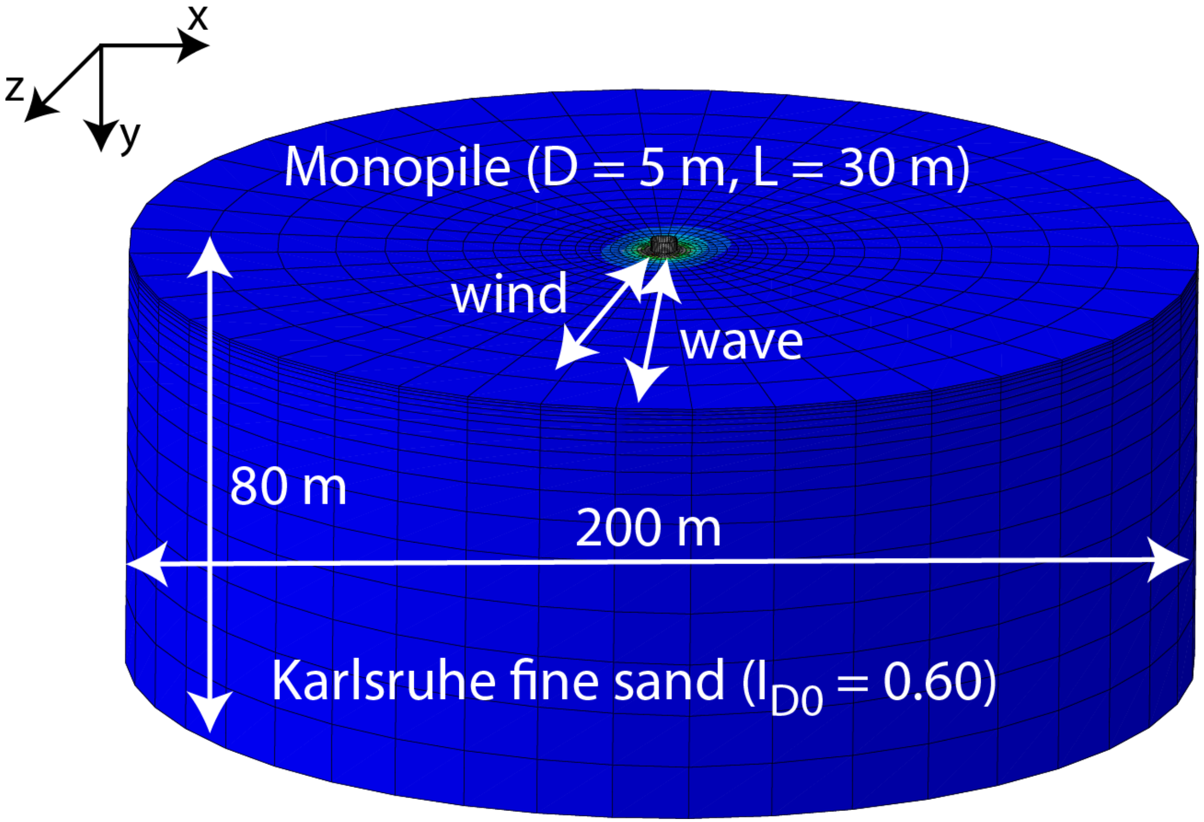
→ Using the definition of the multidimensional amplitude, the data for 1D to 4D strain paths can be described by a single function f_{ampl}

→ Amplitude definition confirmed for 1D to 4D strain paths

Numerical calculations

3D-Model

- Abaqus-Standard
- Interface parameter: $\mu = 0,5$
- Stresses from wind- and wave loads in the Baltic sea next to Sylt:
  - Forces approximately equal in amount
  - Wave with phase shift to wind
  - Wind rotate with $\alpha \leq 60°$ to wave
- Mixed calculation strategy:
  - Hypoplasticity with intergranular strain + HCA model
  - 100.000 stress cycles for wind and wave

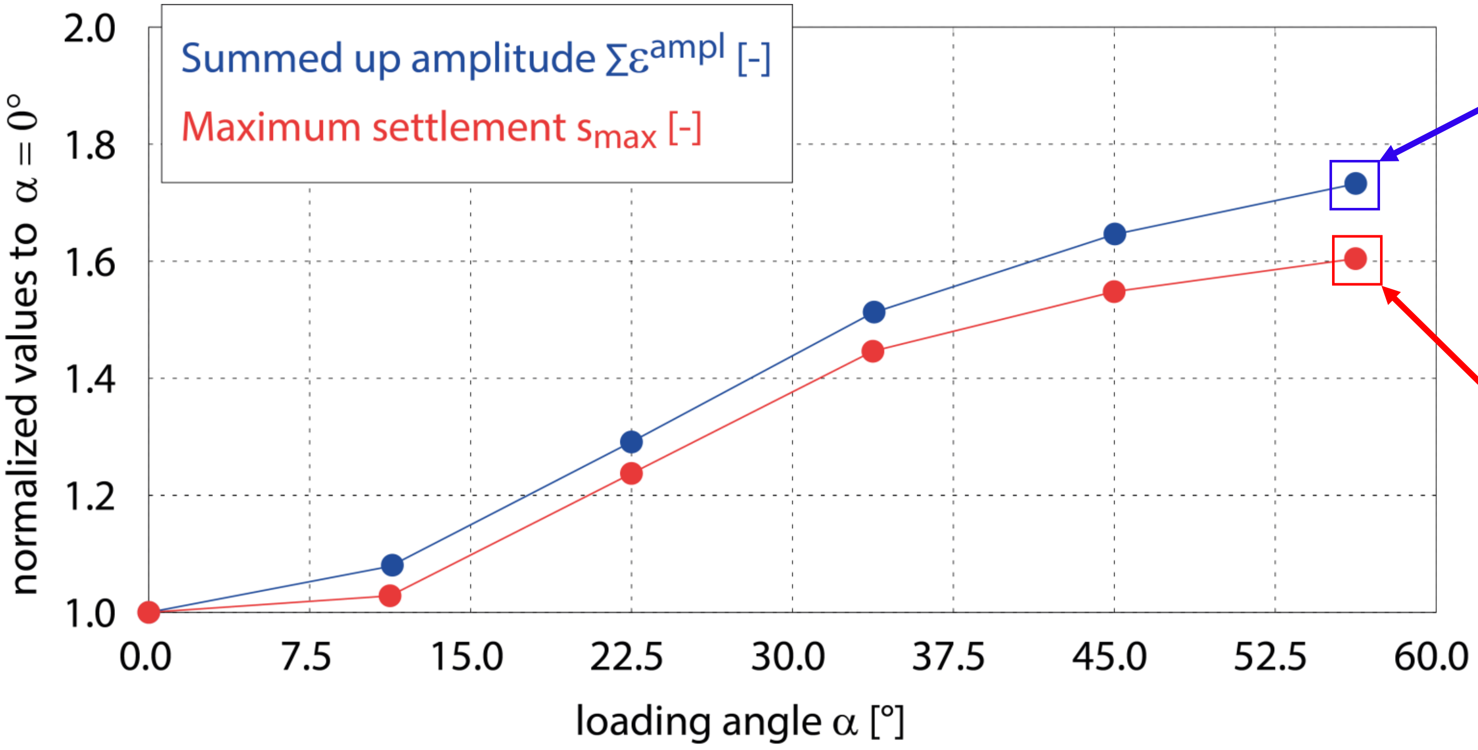


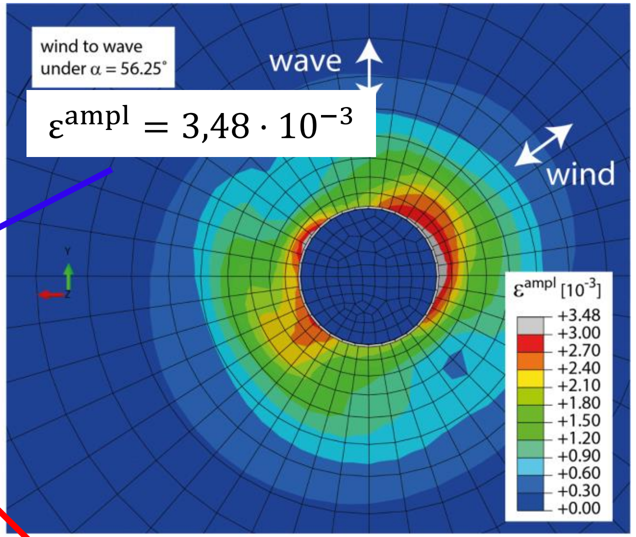
Staubach and Wichtmann (2020)
In: *Computers and Geotechnics*

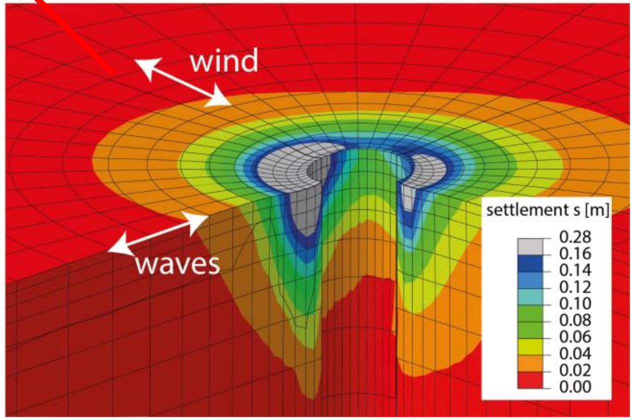
Numerical calculations

Ideal drained conditions

Quantity of the global $\varepsilon^{\mathrm{ampl}}$ distribution:





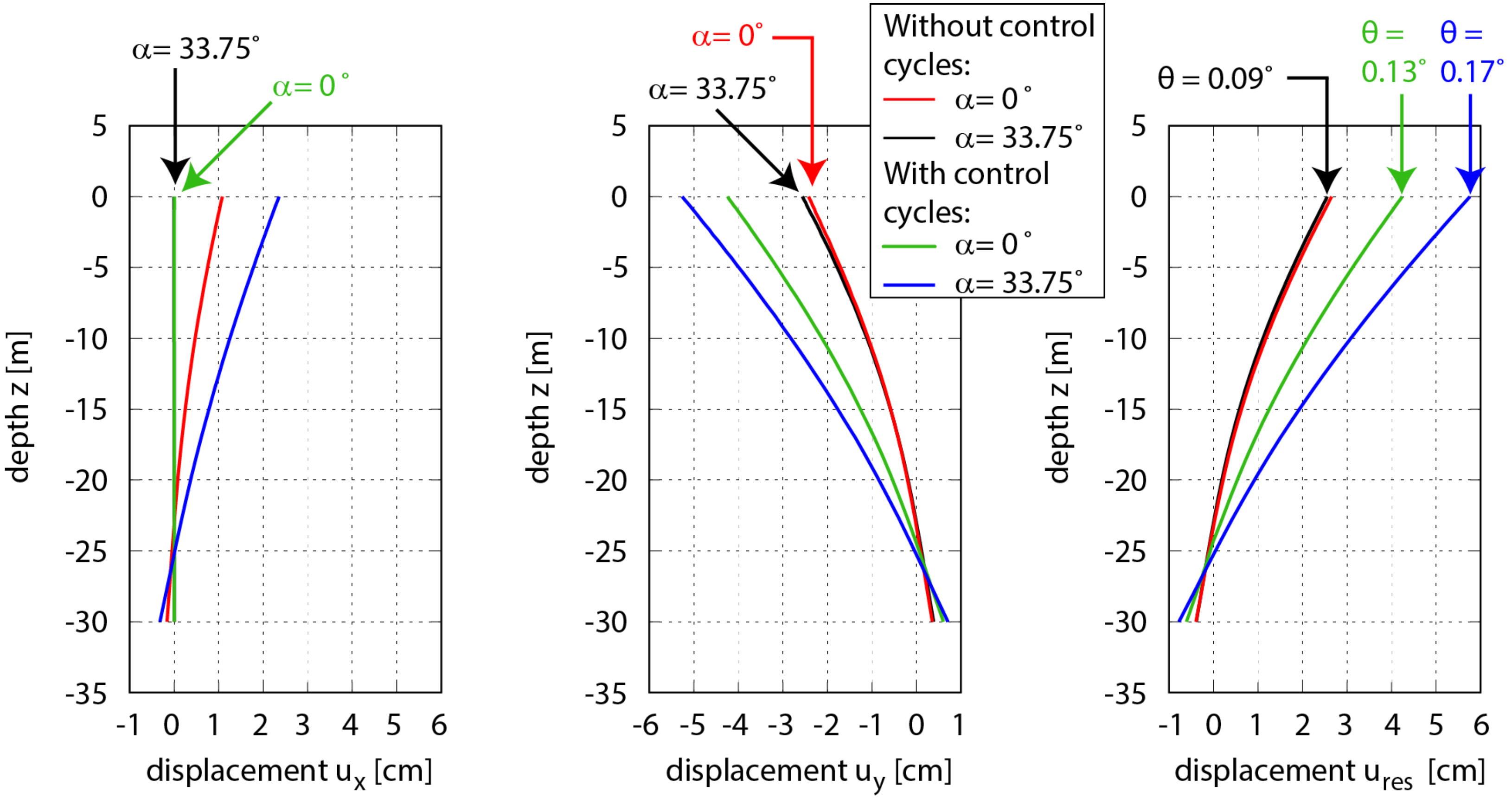


→ Definition of the amplitude $\varepsilon^{\mathrm{ampl}}$ dictates the settlement

Numerical calculations

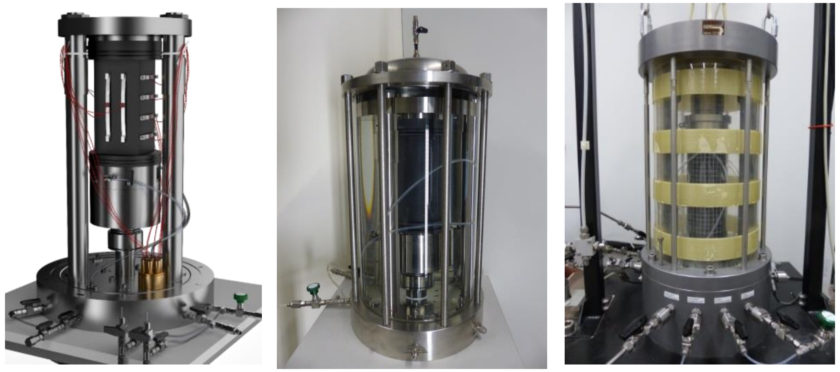
Partial drained conditions

- Abaqus-Standard with C3D8R**P** elements
- Number of cycles $N = 10^5$
  Duration period $T = 1\ s$
  Permeability $k = 10^{-5}\ \frac{m}{s}$
- 2 control cycles after $N = 10^x$ with x = 1, 2, ..., 5
- Consideration of directional dependence and application of control cycles advisable

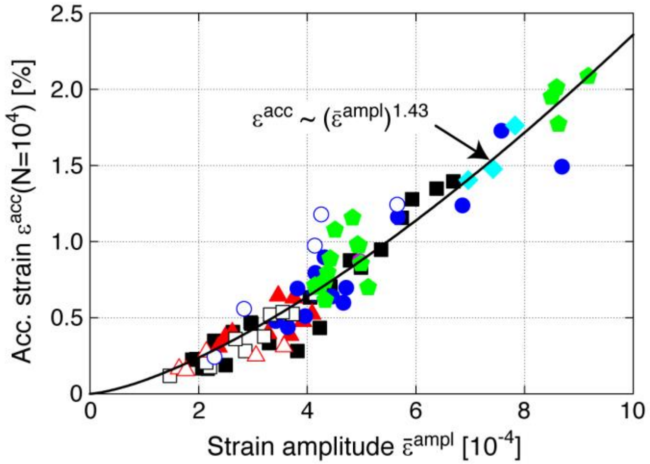


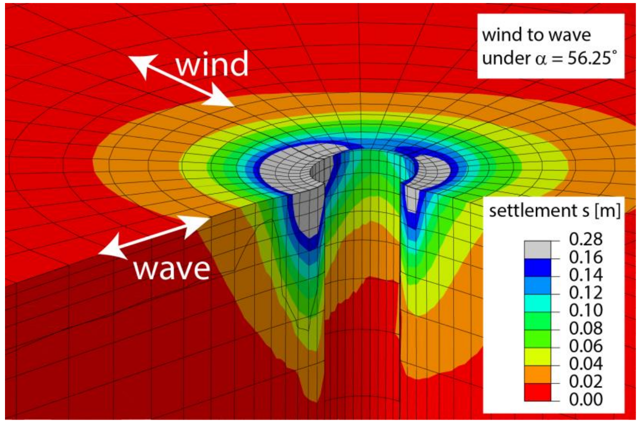
Conclusions

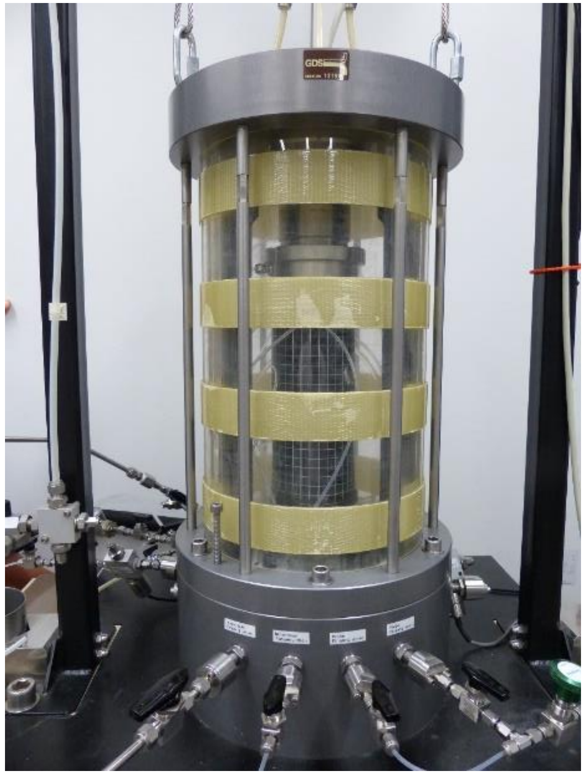
- Experimental proof of the multidimensional definition $\boldsymbol{A}_{\varepsilon} = \sum_{i=1}^{6} R^{(i)}\, \vec{\boldsymbol{r}}^{(i)} \otimes \vec{\boldsymbol{r}}^{(i)}$ in the HCA model.
- Inspectation of 5 constitutive models (implicit + explicit).
- Numerical calculations with a 3D model and the approach of realistic multidimensional loads
- In numerical calculations when considering multidimensional loading, application of control cycles and partially drained ratios, the rotation angle θ can be assumed twice as large.
- Strategy for transfer to similar problems of multidimensional cyclic loading.



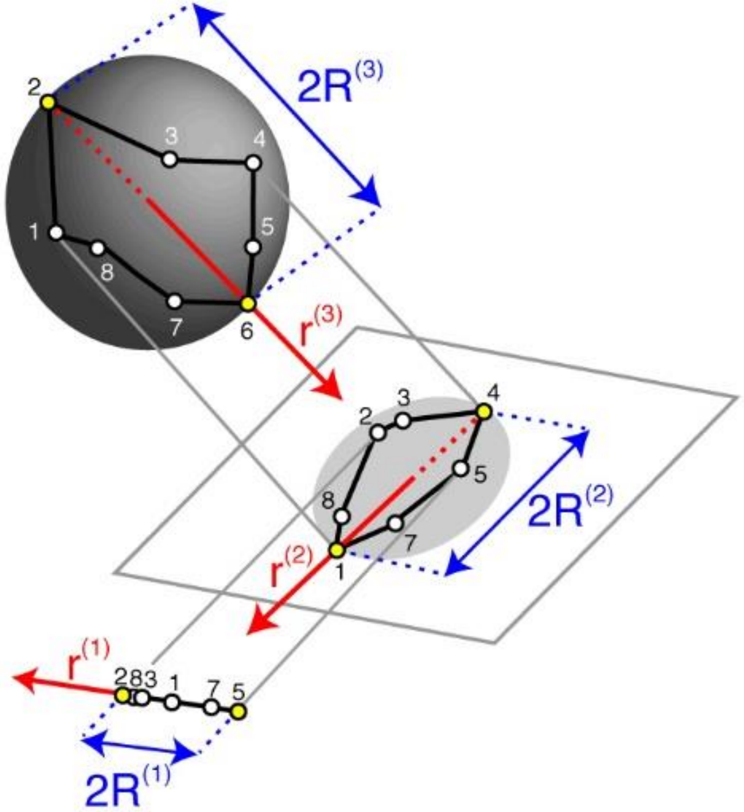
120 cyclic triaxial tests with 1D- to 4D-stresses







Thank you for your attention



$$\mathbf{A}_\varepsilon = \sum_{i=1}^{6} R^{(i)}\, \vec{\mathbf{r}}^{(i)} \otimes \vec{\mathbf{r}}^{(i)}$$