Advanced Methods in modelling cumulative soil behavior for foundation systems of Wind Turbines

Dr.-Ing. Merita Tafili

Chair of Soil Mechanics, Foundation Engineering and Environmental Geotechnics
Ruhr-Universität Bochum, Germany

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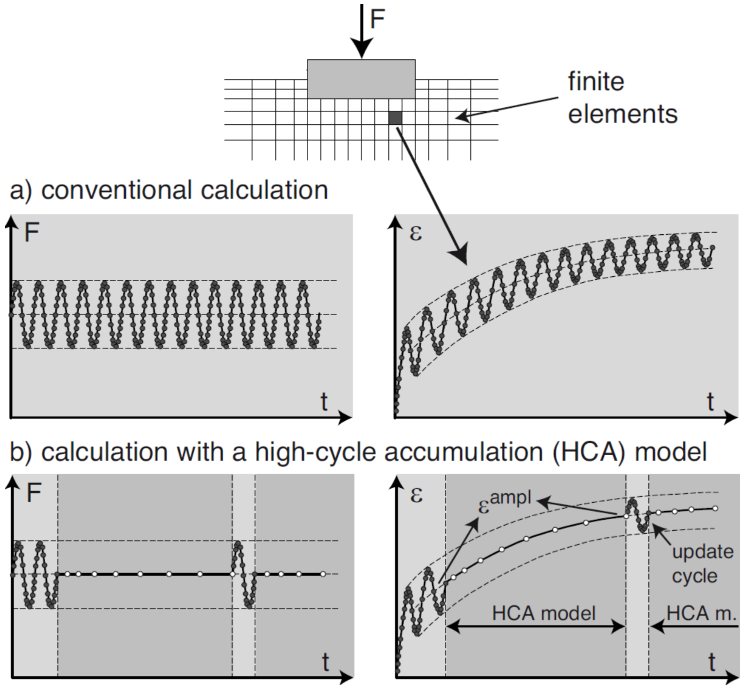

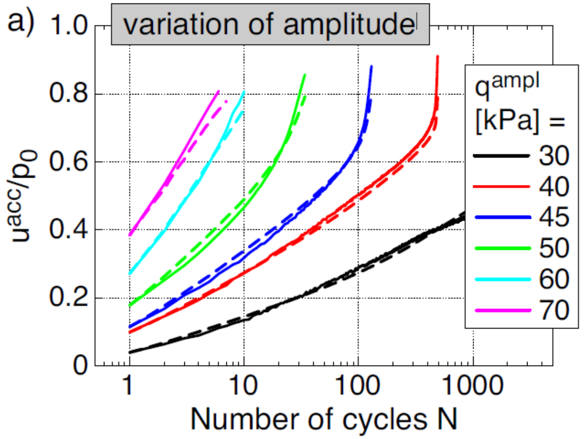

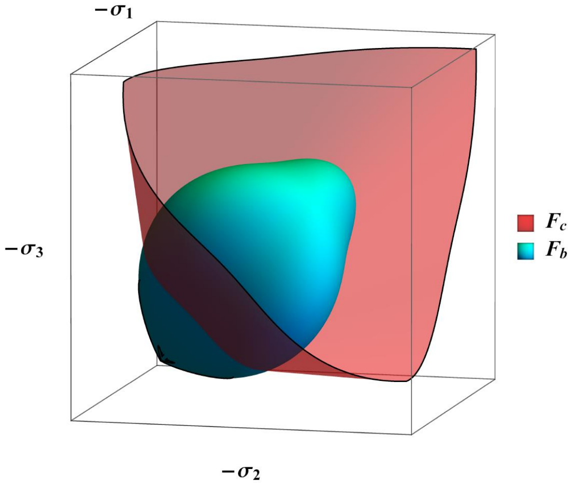

$$F(\sigma,\sigma_B) = \mathbf{w}:\mathbf{w} - \frac{2}{3}M_w^2\left[1-\left(\frac{p}{p_B}\right)^{c_B}\right]\left[1-\sqrt{\frac{3}{2}}\frac{\sqrt{\boldsymbol{\Omega}:\boldsymbol{\Omega}}}{M_\Omega}\right]^2$$

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

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

Outline

- Motivation
- Soil behaviour under cyclic loading
  - sands under undrained and drained triaxial cyclic loading
  - clays under undrained triaxial cyclic loading
- Conventional constitutive models under low to medium-cycle loading
  - Ingredients
  - Constitutive anamnesis model
- High cyclic accumulation (HCA) model
  - HCA for sand
  - HCA for clay
- Back-analysis of centrifuge tests on monopiles in soft clay
- Summary and Conclusions

Motivation

- Cyclic loading from e.g. wind and waves
- Decrease of the effective stress
- Increase of excess pore water pressure
- Decrease of the stiffnes of the soil
- Accumulation of deformation under medium- and high-cycle loading of foundations
- Serviceability problem

Outline

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Soil behaviour under cyclic loading

- Sand

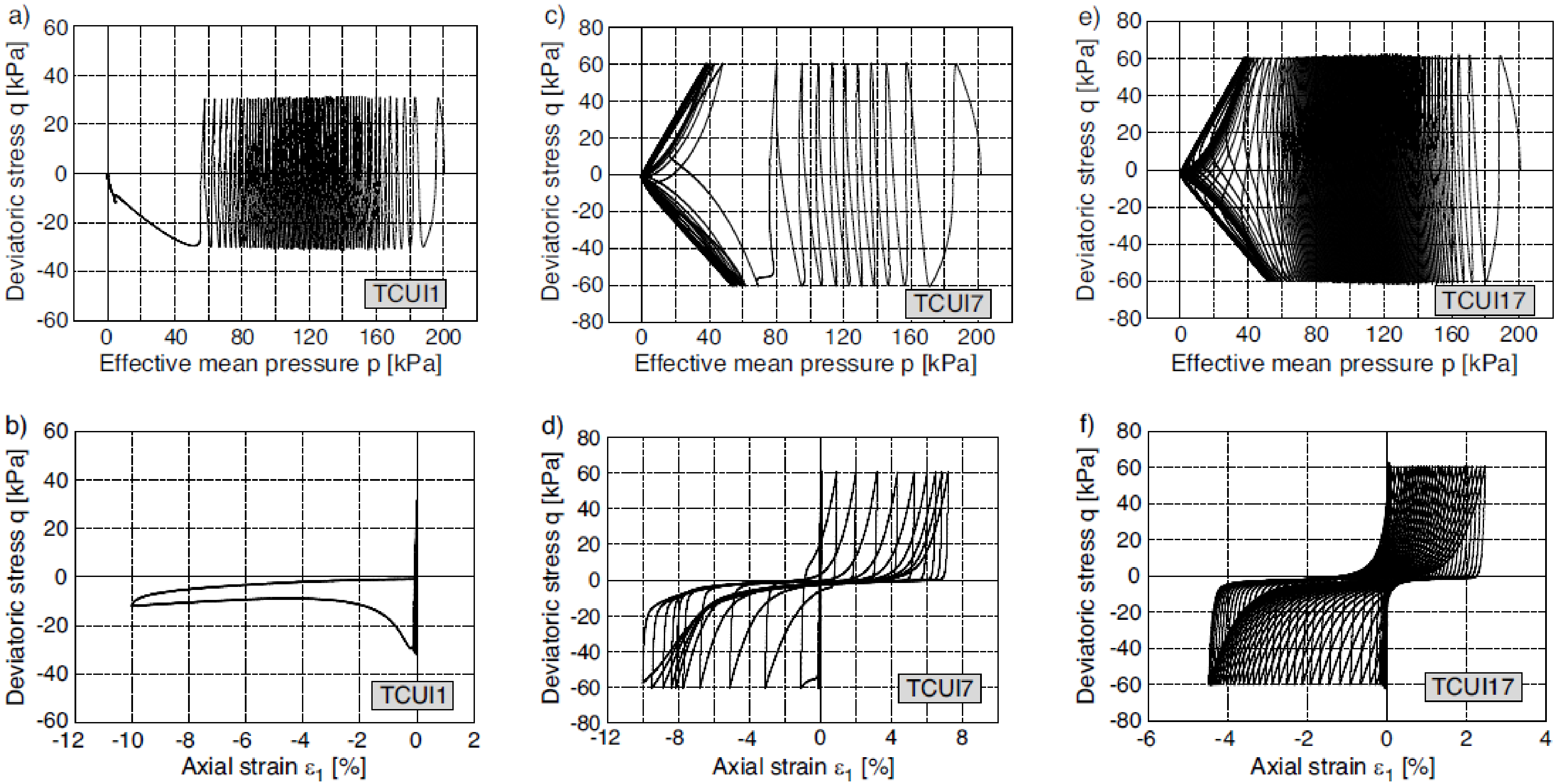
  undrained triaxial tests

  - variation of deviatoric stress amplitude q^{ampl}
  - variation of initial relative density I_{D0}

$q^{ampl} \uparrow \Rightarrow N \downarrow$

$I_{D0} \uparrow \Rightarrow N \uparrow$

$q^{ampl} = 30$ kPa, $I_{D0} = 0.27$ | $q^{ampl} = 60$ kPa, $I_{D0} = 0.67$ | $q^{ampl} = 60$ kPa, $I_{D0} = 0.87$



(Wichtmann&Triantafyllidis 2016)

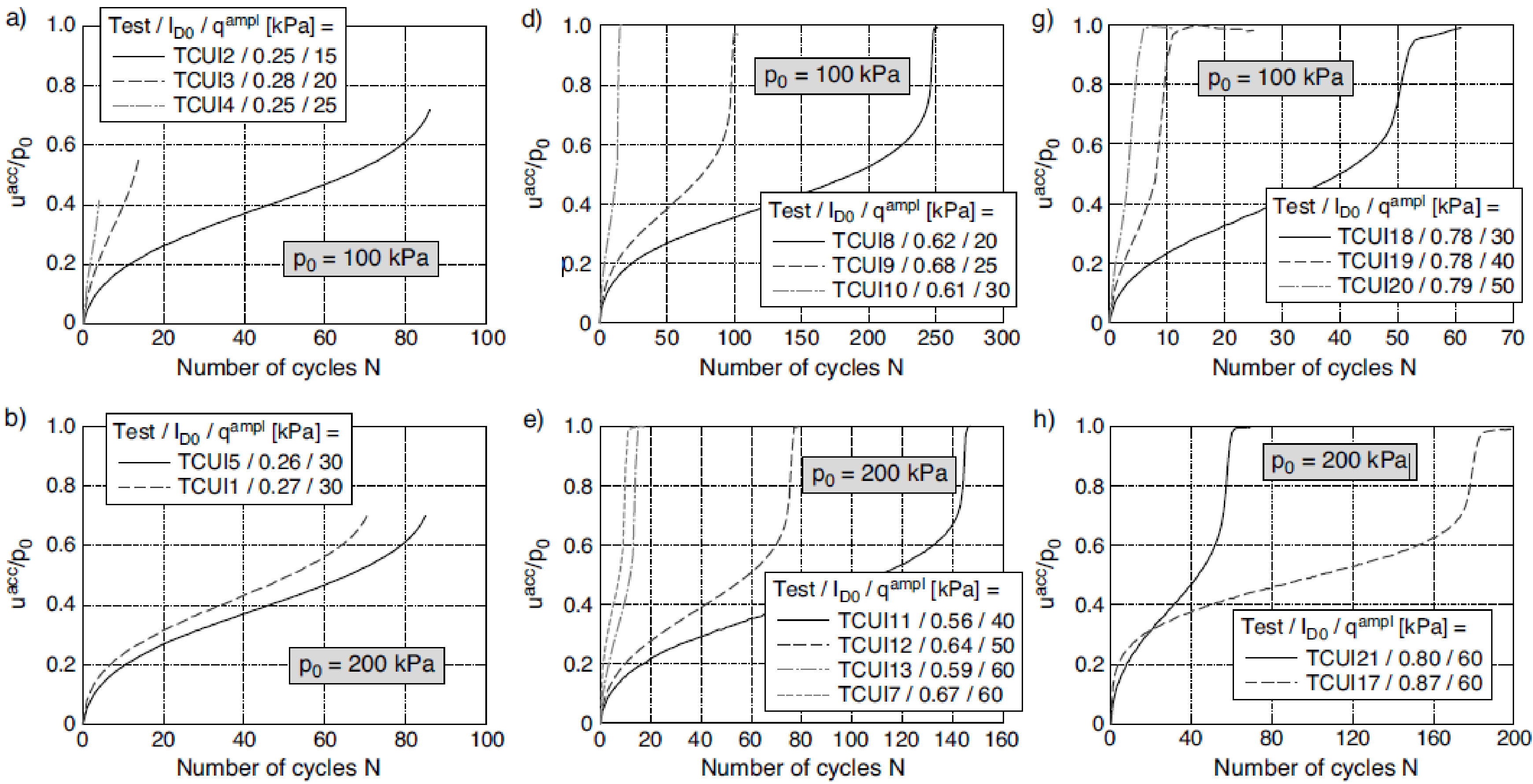
Soil behaviour under cyclic loading

- Sand
  undrained triaxial tests
  - variation of deviatoric stress amplitude q^{ampl}
  - variation of initial relative density I_{D0}
  - variation of initial mean pressure p_0

$q^{ampl} \uparrow \Rightarrow N \downarrow \Rightarrow u^{acc} \uparrow$

$I_{D0} \uparrow \Rightarrow N \uparrow \Rightarrow u^{acc} \downarrow$

$p_0 \uparrow \Rightarrow N \uparrow \Rightarrow u^{acc} \downarrow$



(Wichtmann&Triantafyllidis 2016)

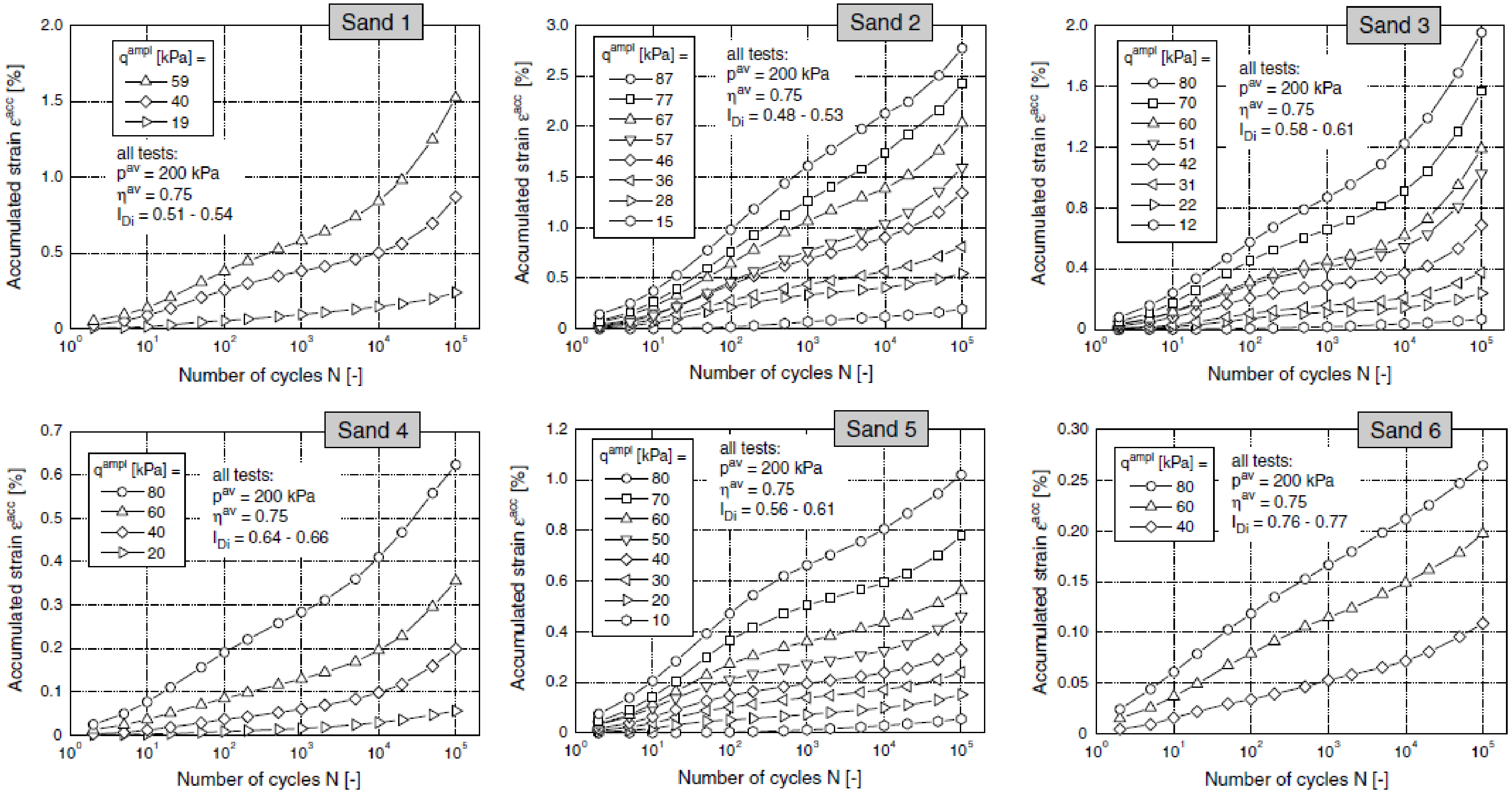
Soil behaviour under cyclic loading

- Sand
  drained triaxial tests
  - variation of deviatoric stress amplitude q^{ampl}
  - variation of initial relative density I_{D0}
  - variation of initial stress ratio η_0

$q^{ampl} \uparrow \Rightarrow N \downarrow \Rightarrow \varepsilon^{acc} \uparrow$

$I_{D0} \uparrow \Rightarrow N \uparrow \Rightarrow \varepsilon^{acc} \downarrow$

$\eta_0 \uparrow \Rightarrow N \uparrow \Rightarrow \varepsilon^{acc} \downarrow$



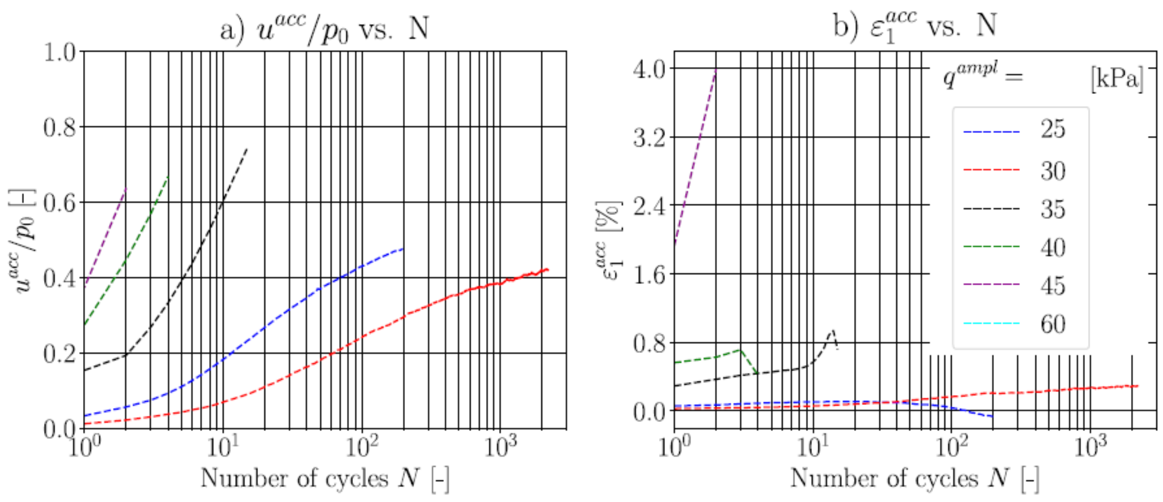
(Wichtmann et al. 2009)

Soil behaviour under cyclic loading

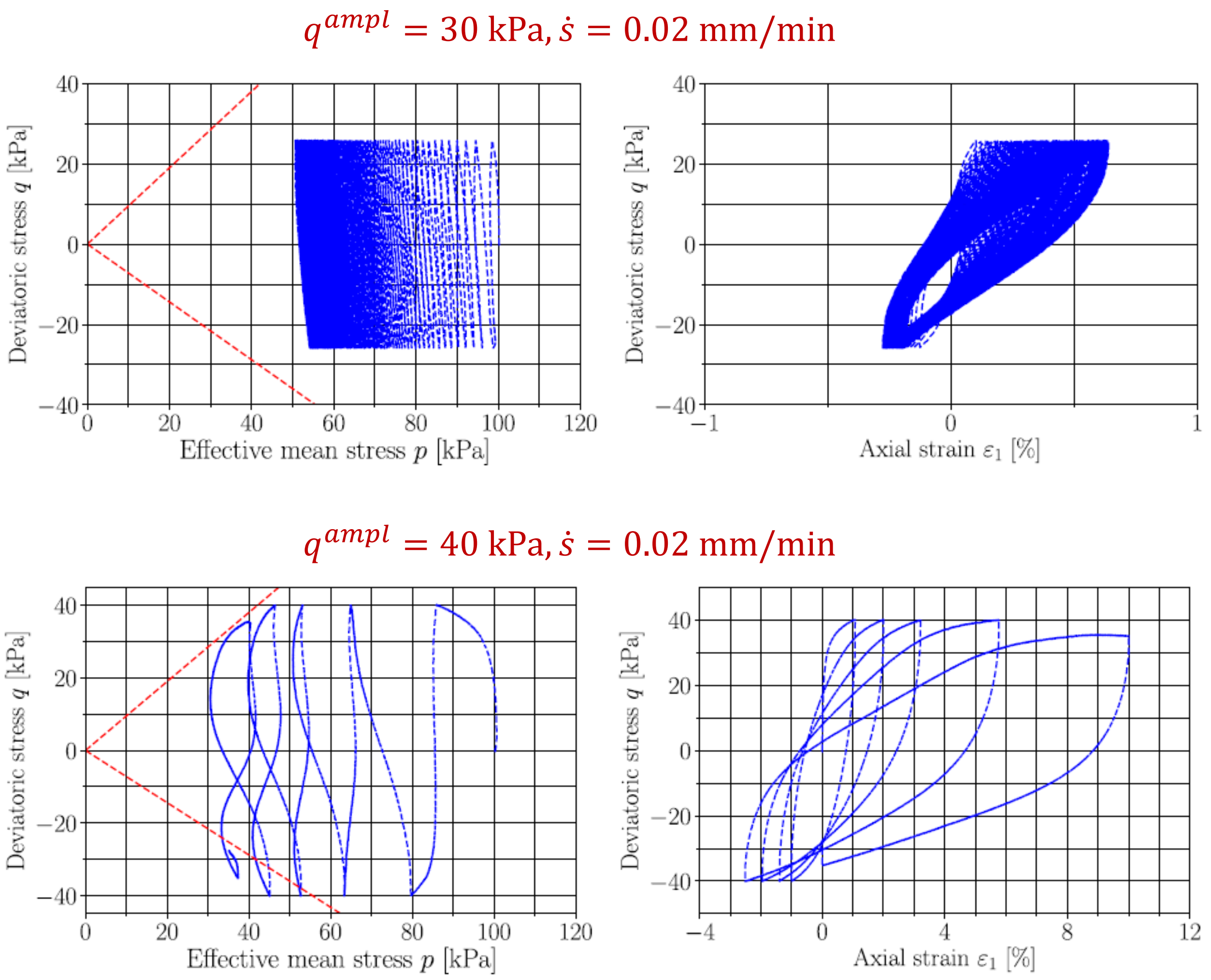
- Clay

  undrained triaxial tests

  - variation of deviatoric stress amplitude q^{ampl}



$q^{ampl} \uparrow \Rightarrow N \downarrow \Rightarrow \varepsilon^{acc} \uparrow$



(Tafili et al. 2019, 2020)

Soil behaviour under cyclic loading

- Clay

  undrained triaxial tests

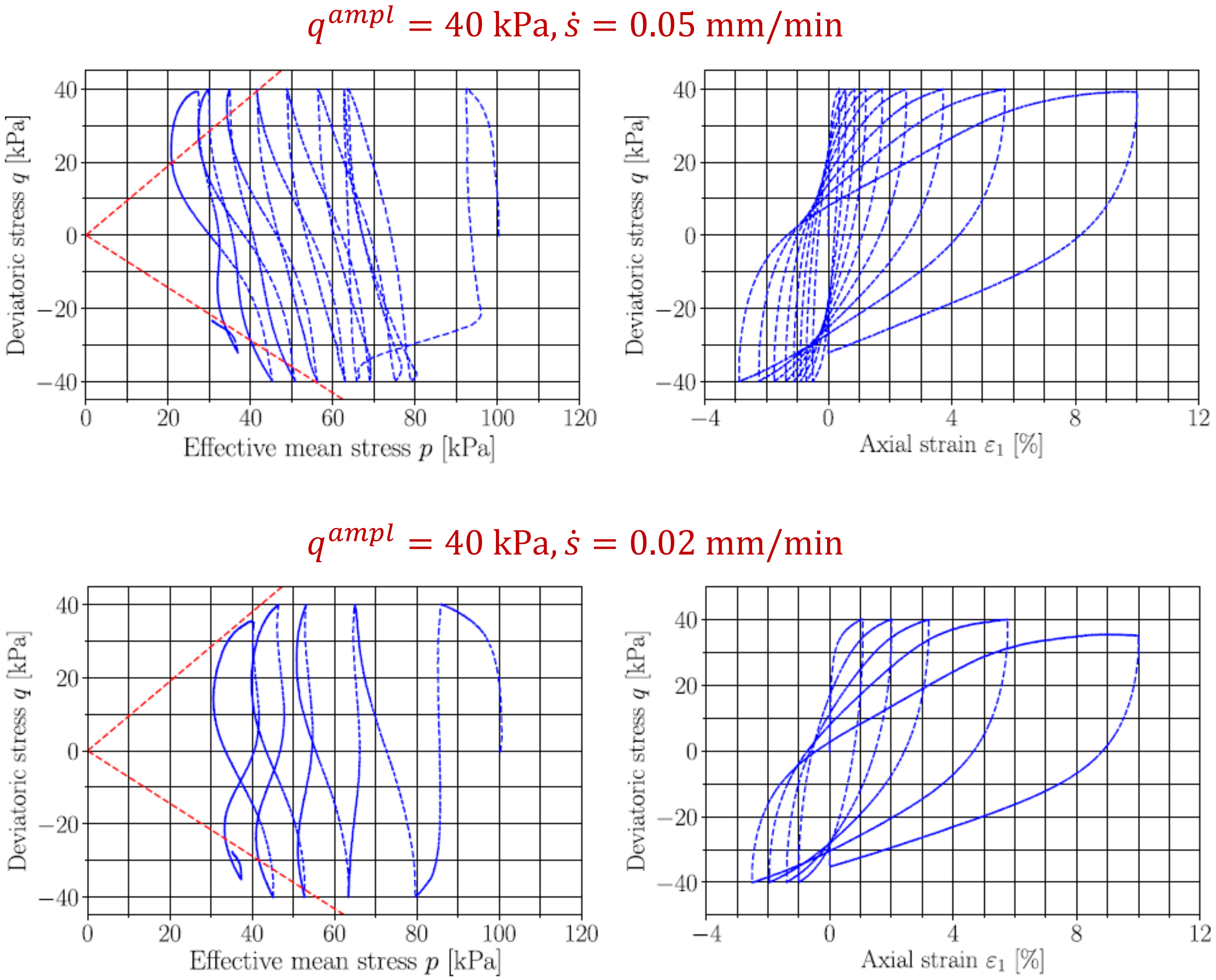
  - variation of deviatoric stress amplitude q^{ampl}
  - variation of initial void ratio e_0
  - variation of initial stress ratio η_0
  - variation of displacement rate $\dot{s}$

$$q^{ampl} \uparrow \Rightarrow N \downarrow \Rightarrow \varepsilon^{acc} \uparrow$$

$$\dot{s} \uparrow \Rightarrow N \uparrow \Rightarrow \varepsilon^{acc} \downarrow$$

$$\eta_0 \uparrow \Rightarrow N \uparrow \Rightarrow \varepsilon^{acc} \downarrow$$

$$e_0 \uparrow \Rightarrow N \downarrow \Rightarrow \varepsilon^{acc} \uparrow$$



(Tafili et al. 2019, 2020)

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  - HCA for clay
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Conventional constitutive models under low to medium-cycle loading

- Ingredients

$$\dot{p} = K\left(\dot{\varepsilon}_v - \dot{\varepsilon}_v^{hp} - \dot{\varepsilon}_v^{vis}\right)$$

- Bulk modulus
  - Virgin loading $\dot{\varepsilon}_v = -\frac{\dot{e}}{1+e} \Rightarrow K = \frac{p}{\lambda}\frac{(1+e)}{(1-Y_{min})}$
- Non-linearity
  - Unloading and reloading

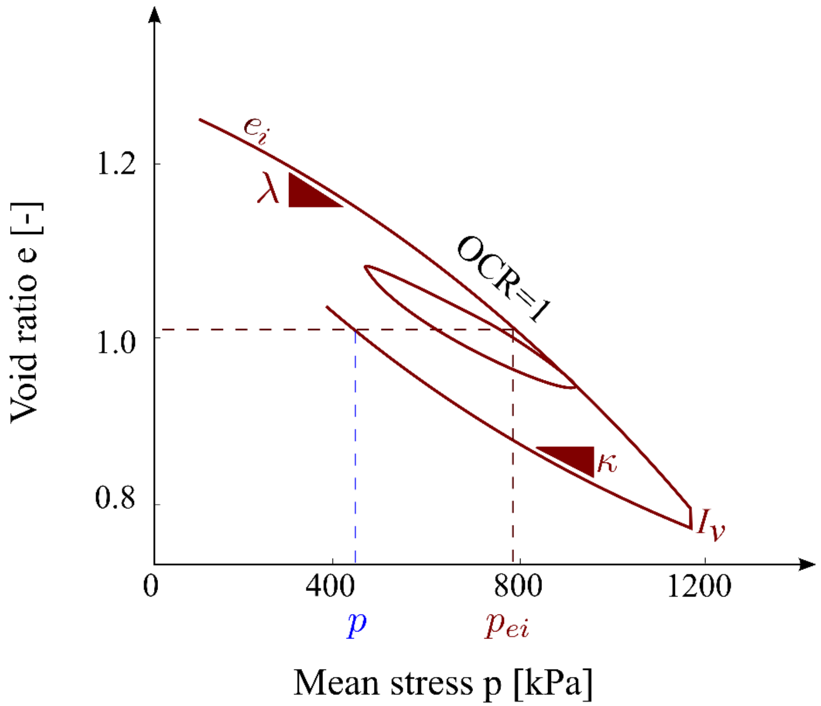
$$\dot{e} = -\kappa\frac{\dot{p}}{p} \Rightarrow Y_{min} = \frac{\lambda-\kappa}{\lambda+\kappa}$$

- Previous loading
  - Normally consolidated line $\Rightarrow$ OCR = 1

$$e_i = (1+e_{i0})\left(\frac{p_{i0}}{p}\right)^{\lambda} - 1$$

$$\Rightarrow p_{ei} = p_{i0}\left(\frac{1+e_{i0}}{1+e}\right)^{1/\lambda}$$

$$\mathrm{OCR} = \frac{p_{ei}}{p}$$



Conventional constitutive models under low to medium-cycle loading

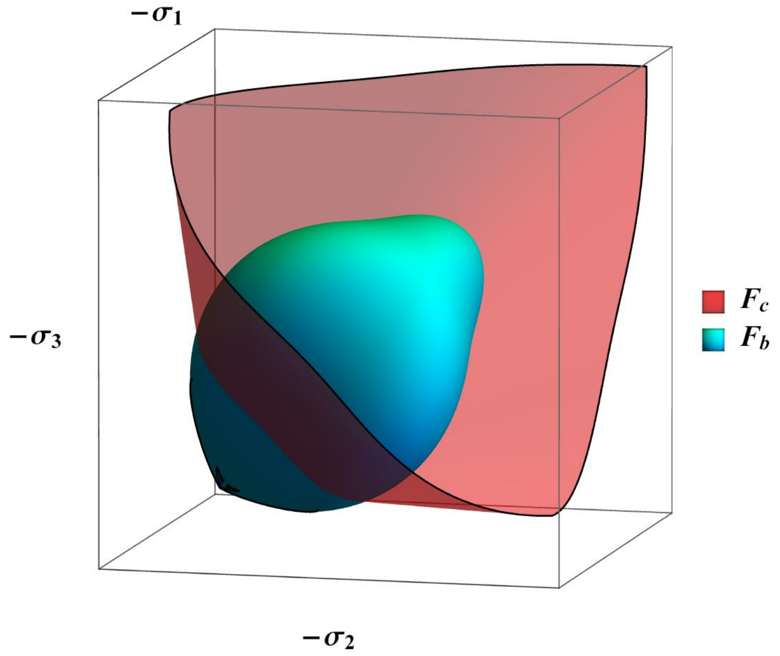
- Ingredients

$$\dot{\boldsymbol{\sigma}} = \mathrm{E}:\left(\dot{\boldsymbol{\varepsilon}} - \dot{\boldsymbol{\varepsilon}}^{hp} - \dot{\boldsymbol{\varepsilon}}^{vis}\right) = \mathrm{E}:\left(\dot{\boldsymbol{\varepsilon}} - Y\mathbf{m}\|\dot{\boldsymbol{\varepsilon}}\| - I_v\lambda\left(\frac{1}{\mathrm{OCR}}\right)^{1/I_v}\mathbf{m}\right)$$

  - Stiffness tensor E
  - Critical state and Dilatancy rule
  - Loading surface
    - 3D: $F_b(\boldsymbol{\sigma}) = \hat{\boldsymbol{\sigma}}^*:\hat{\boldsymbol{\sigma}}^* - \frac{2}{3f_b^2(M(\theta_\sigma))^2} = 0$

$$f_b = f(e, e_i, e_c),$$

$$\mathrm{OCR} = \frac{p_{ei}}{p_{ei}^+},\ p_{ei}^+ = p_{i0}\left(\frac{1+e_{i0}}{1+e^+}\right)^{1/\lambda}$$



Conventional constitutive models under low to medium-cycle loading

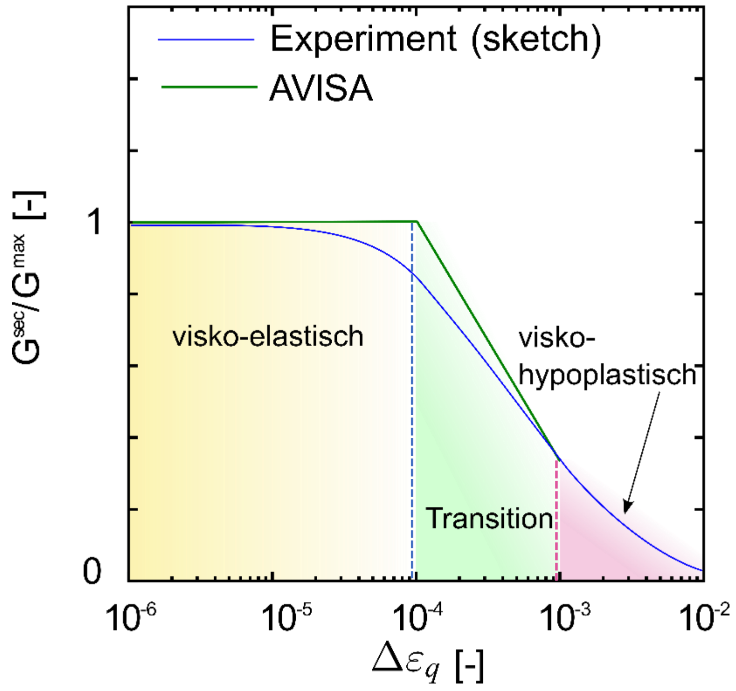
- Ingredients

$$\dot{\boldsymbol{\sigma}} = \mathsf{E} : (\dot{\boldsymbol{\varepsilon}} - \dot{\boldsymbol{\varepsilon}}^{hp} - \dot{\boldsymbol{\varepsilon}}^{vis}) = \mathsf{E} : \left(\dot{\boldsymbol{\varepsilon}} - Y \mathbf{m} \|\dot{\boldsymbol{\varepsilon}}\| - I_v \lambda \left(\frac{1}{\mathrm{OCR}} \right)^{1/I_v} \mathbf{m} \right)$$

- Stiffness tensor E ✓
- Critical state and Dilatancy rule ✓
- Loading surface ✓

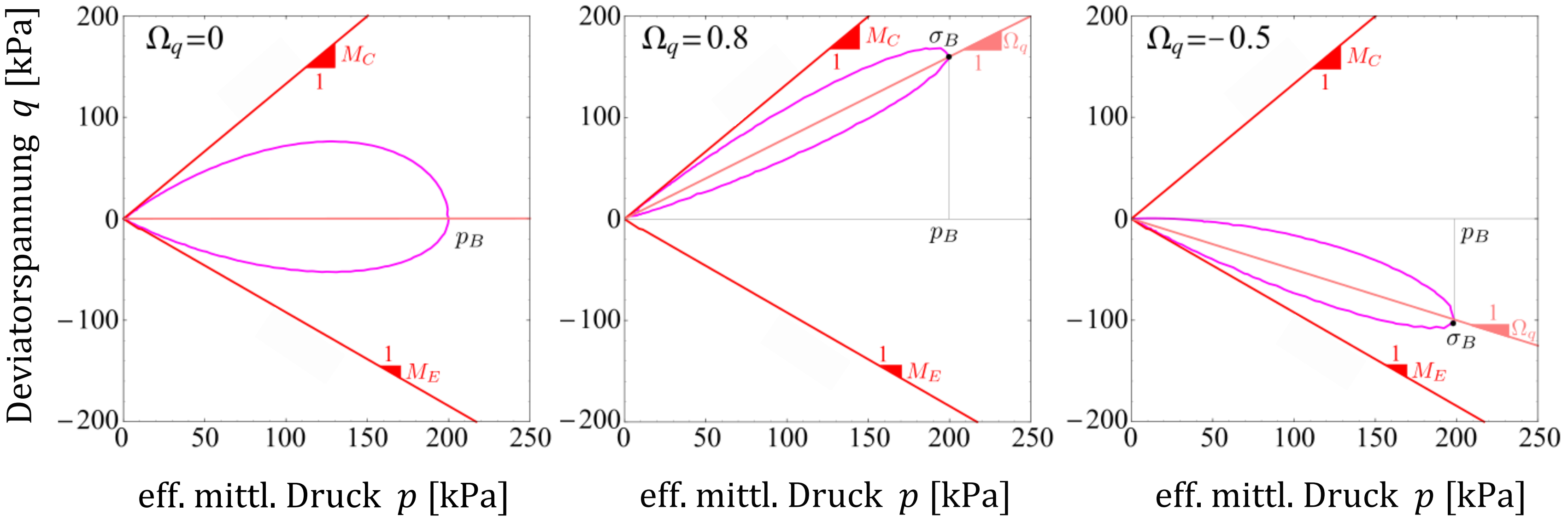
- Shear modulus degradation
- Stiffness at small strains
- Anamnesis and
- Historiotropy of the soil

➡ incremental approach not sufficient



Conventional constitutive models under low to medium-cycle loading

- Constitutive anamnesis model (PhD Tafili 2019)
  - Historiotropic surface with
  - evolving size ⇒ shear modulus degradation
  - rotating bisector ⇒ induced anisotropy

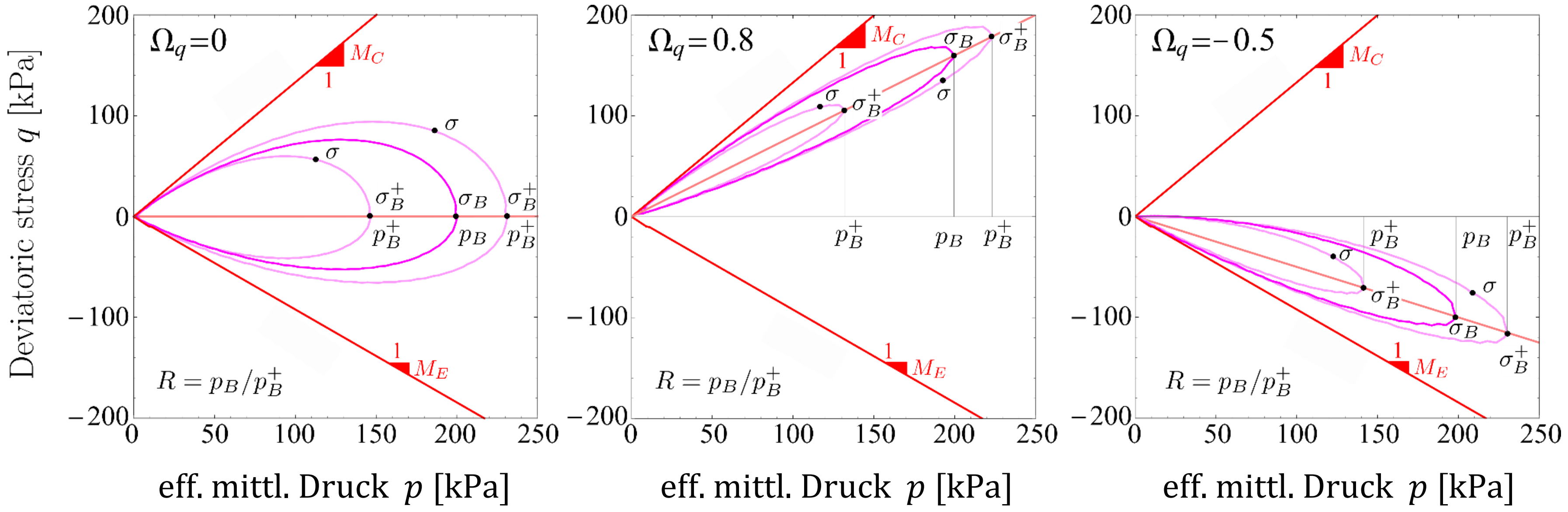


$$F(\sigma, \sigma_B) = \mathbf{w}:\mathbf{w} - \frac{2}{3}M_w^2\left[1-\left(\frac{p}{p_B}\right)^{c_B}\right]\left[1-\sqrt{\frac{3}{2}}\frac{\sqrt{\mathbf{\Omega}:\mathbf{\Omega}}}{M_\Omega}\right]^2$$

$$\boldsymbol{\sigma}_B = p_B(-\mathbf{1}+\mathbf{\Omega})$$
$$\mathbf{w} = \hat{\boldsymbol{\sigma}}^* - \mathbf{\Omega}$$
$$\hat{\boldsymbol{\sigma}}^* = \boldsymbol{\sigma}^*/p$$

Conventional constitutive models under low to medium-cycle loading

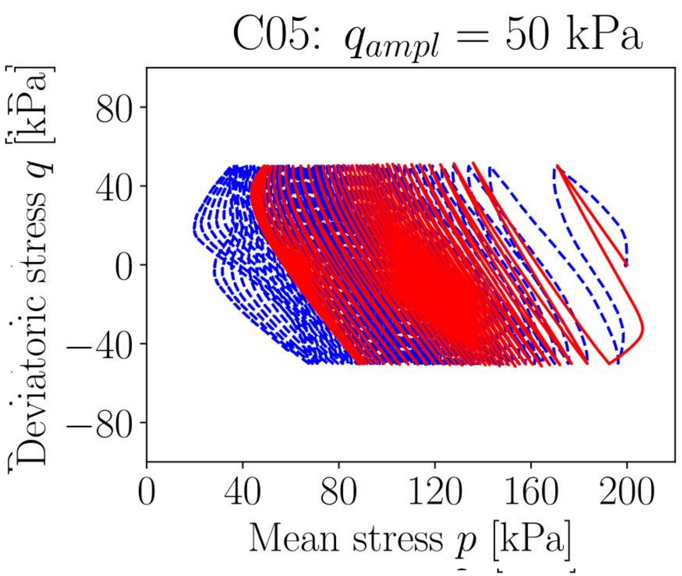
- Constitutive anamnesis model (PhD Tafili 2019)
  - loading surface (back stress) $\boldsymbol{\sigma}_B = p_B(-\mathbf{1} + \boldsymbol{\Omega})$
  - isotropic size $\dot{p}_B = -\frac{p_B}{\lambda}\mathrm{tr}(\dot{\boldsymbol{\varepsilon}}) - C_2(p - p_B)\|\dot{\boldsymbol{\varepsilon}}^*\|R^{-n_0}$
  - Bisector inclination $\dot{\boldsymbol{\Omega}} = C_2(\hat{\boldsymbol{\sigma}}^* - \boldsymbol{\Omega})\|\dot{\boldsymbol{\varepsilon}}\|R^{-n_0}$



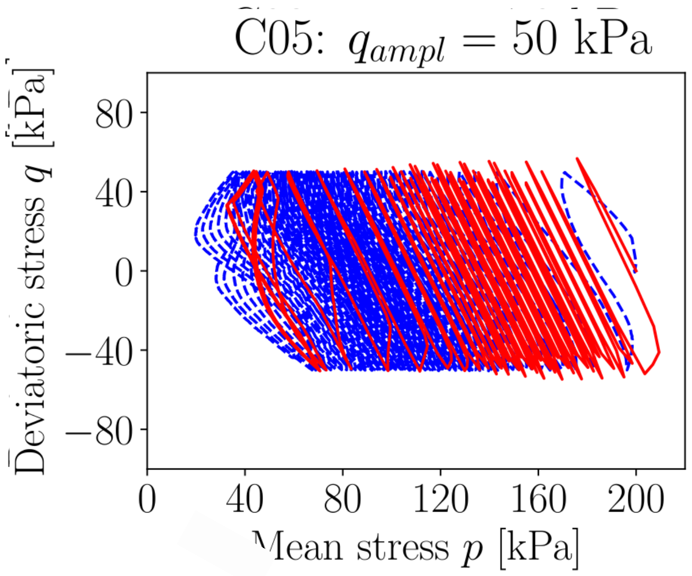
Conventional constitutive models under low to medium-cycle loading

- Constitutive anamnesis model – Simulation of a triaxial cyclic test

AVISA



Anamnese

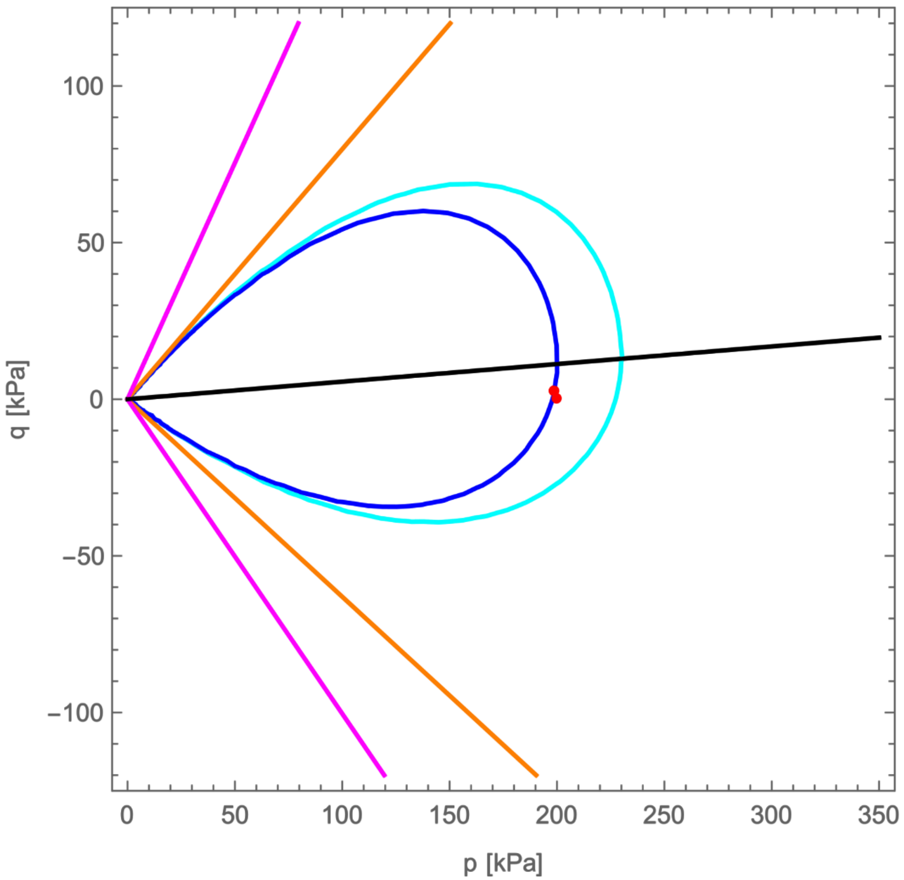


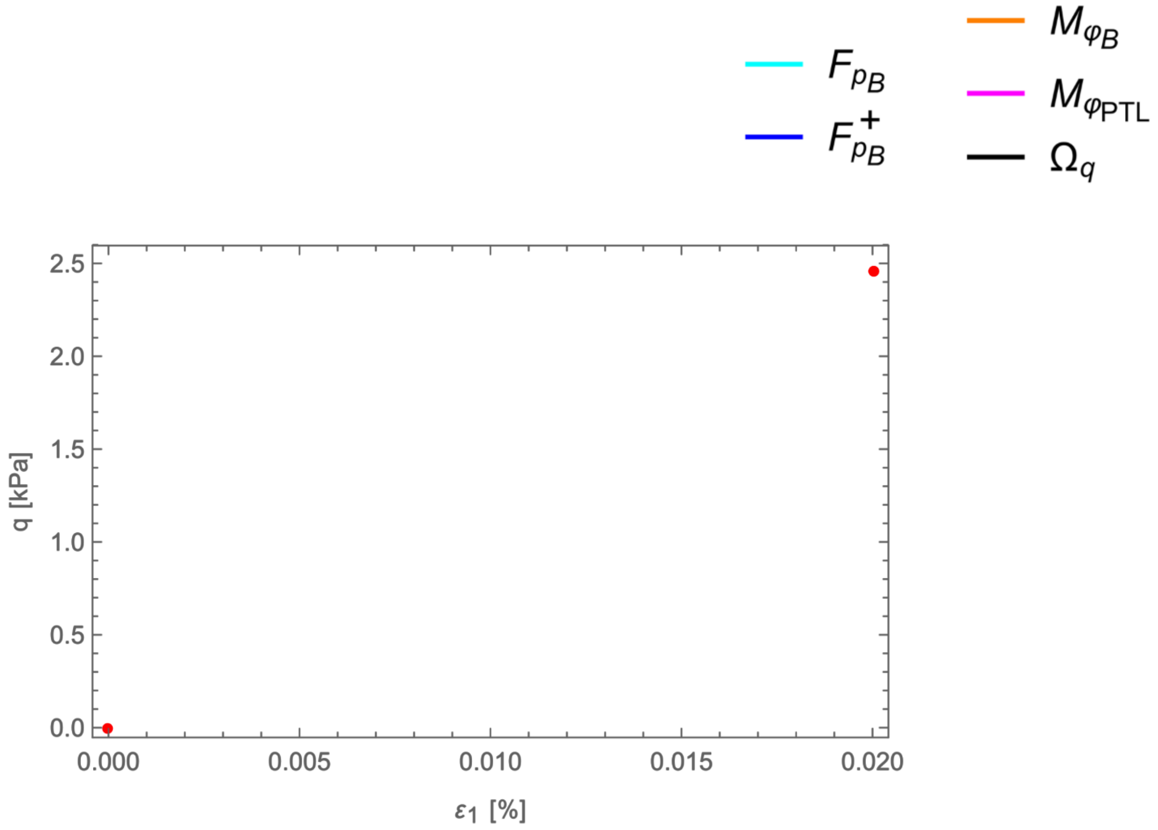
(Data: Tafili et al. 2019)

- accurate description of 8-shaped hystheresis
- accurate reproduction of the number of cycles N up to $||\varepsilon_1|| \leq 10$ %

Conventional constitutive models under low to medium-cycle loading

- Constitutive anamnesis model – Development of the hisotriotropic surface for $q_{ampl} = 70\ \mathrm{kPa}$





High cyclic accumulation (HCA) model

- HCA for sand (Niemunis et al. 2005)

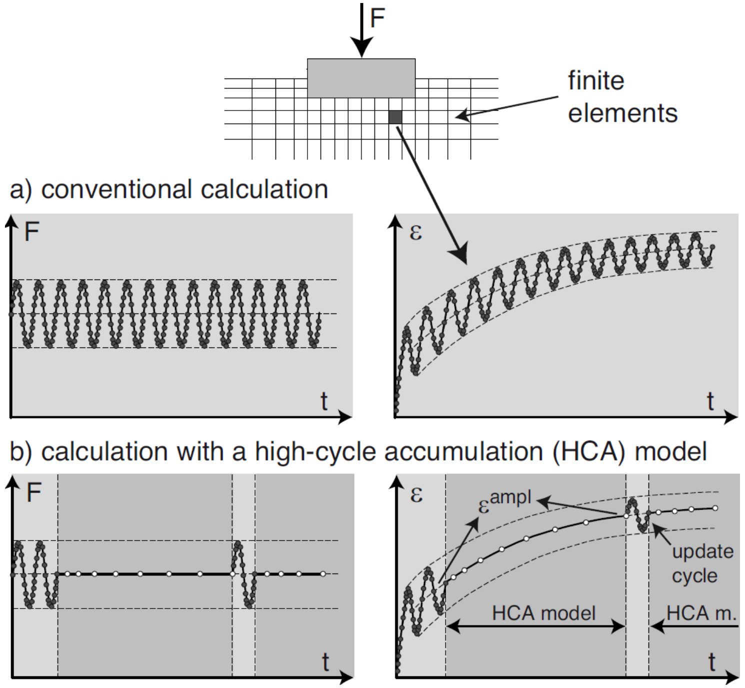
$$\dot{\boldsymbol{\sigma}} = \mathrm{E} : \left(\dot{\boldsymbol{\varepsilon}} - \dot{\boldsymbol{\varepsilon}}^{acc} - \dot{\boldsymbol{\varepsilon}}^{pl}\right) \text{ with } \dot{\sqcup} = \partial \sqcup / \partial N$$

↓

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

↓

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



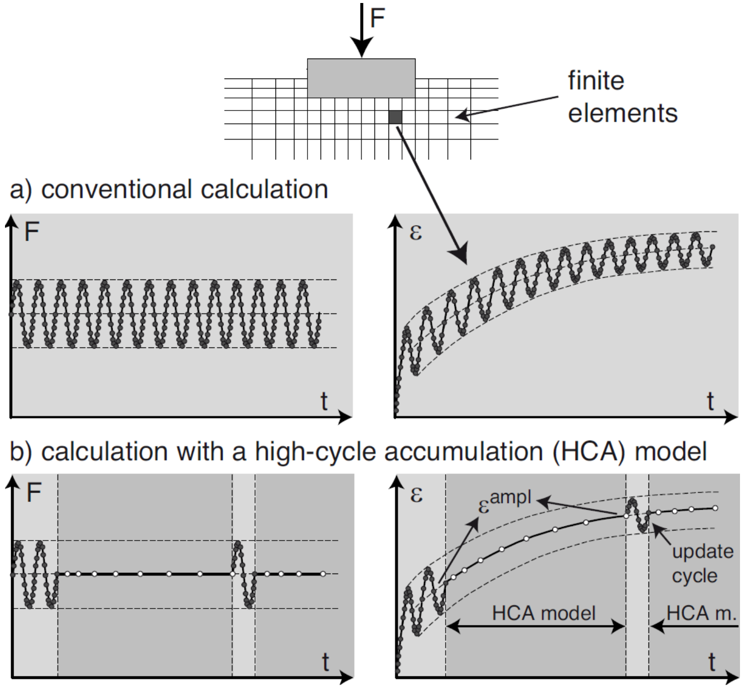
High cyclic accumulation (HCA) model

- HCA for clay (Staubach et al. 2021)
  - Intensity of accumulation:

$$\dot{\boldsymbol{\sigma}} = \mathrm{E}:\left(\dot{\boldsymbol{\varepsilon}} - \dot{\boldsymbol{\varepsilon}}^{acc} - \dot{\boldsymbol{\varepsilon}}^{pl}\right) \text{ with } \dot{\sqcup} = \partial \sqcup / \partial N$$

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

$$\dot{\varepsilon}^{acc} = f_{ampl}\dot{f}_N f_e f_\eta f_{OCR} f_f$$



High cyclic accumulation (HCA) model

- HCA for clay (Staubach et al. 2021)
  - Intensity of accumulation:
    - Influence of the strain amplitude

$$\dot{\boldsymbol{\sigma}} = \mathrm{E}:\left(\dot{\boldsymbol{\varepsilon}} - \dot{\boldsymbol{\varepsilon}}^{acc} - \dot{\boldsymbol{\varepsilon}}^{pl}\right) \text{ with } \dot{\square} = \partial \square / \partial N$$

↓

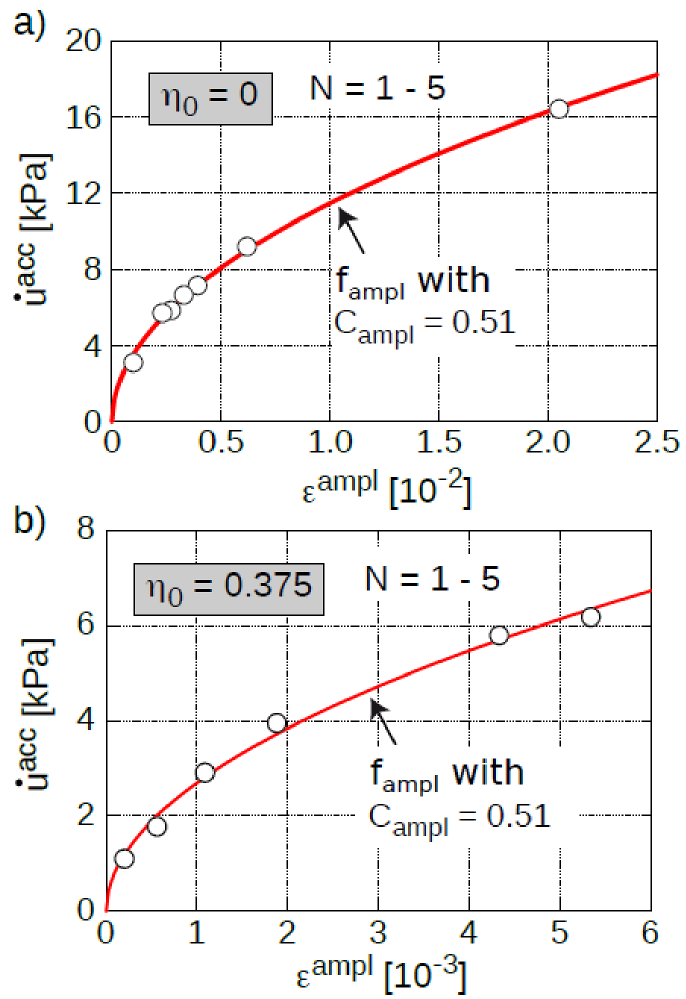
$$\dot{\boldsymbol{\varepsilon}}^{acc} = \dot{\varepsilon}^{acc}\boldsymbol{m}$$

↓

$$\dot{\varepsilon}^{acc} = f_{ampl}\dot{f}_N f_e f_\eta f_{OCR} f_f$$

↓

$$f_{ampl} = \left(\frac{\varepsilon^{ampl}}{\varepsilon^{ampl}_{ref}}\right)^{C_{ampl}}$$



High cyclic accumulation (HCA) model

- HCA for clay (Staubach et al. 2021)
  - Intensity of accumulation:
    - Influence of the cyclic preloading

$$\dot{\boldsymbol{\sigma}} = \mathrm{E} : \left(\dot{\boldsymbol{\varepsilon}} - \dot{\boldsymbol{\varepsilon}}^{acc} - \dot{\boldsymbol{\varepsilon}}^{pl}\right) \text{ with } \dot{\sqcup} = \partial \sqcup / \partial N$$

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

$$\dot{\varepsilon}^{acc} = f_{ampl} \dot{f}_N f_e f_\eta f_{OCR} f_f$$

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

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

$$\dot{f}_N^B = C_{N1} C_{N3}$$

High cyclic accumulation (HCA) model

- HCA for clay (Staubach et al. 2021)
  - Intensity of accumulation:
    - Influence of the void ratio

$$\dot{\boldsymbol{\sigma}} = \mathrm{E}:\left(\dot{\boldsymbol{\varepsilon}} - \dot{\boldsymbol{\varepsilon}}^{acc} - \dot{\boldsymbol{\varepsilon}}^{pl}\right) \text{ with } \dot{\sqcup} = \partial \sqcup / \partial N$$

$$\downarrow$$

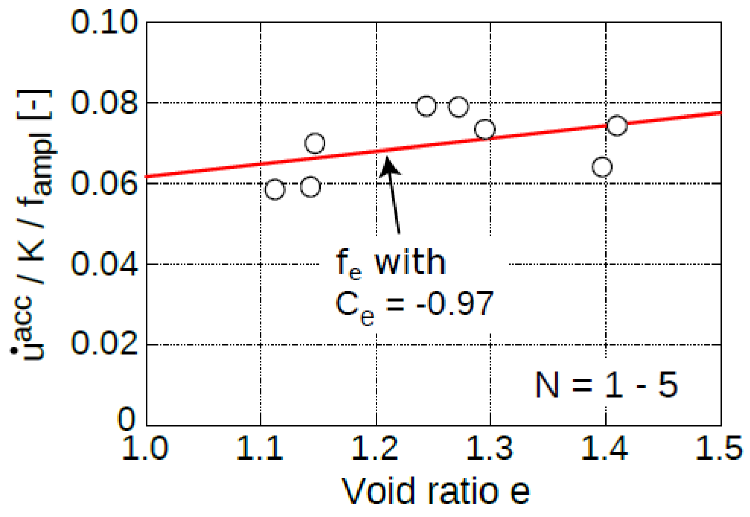
$$\dot{\boldsymbol{\varepsilon}}^{acc} = \dot{\varepsilon}^{acc}\boldsymbol{m}$$

$$\downarrow$$

$$\dot{\varepsilon}^{acc} = f_{ampl}\dot{f}_N f_e f_\eta f_{OCR} f_f$$

$$\downarrow$$

$$f_e = \frac{(C_e - e)^2}{1 + e}\,\frac{1 + e_{ref}}{\left(C_e - e_{ref}\right)^2}$$



High cyclic accumulation (HCA) model

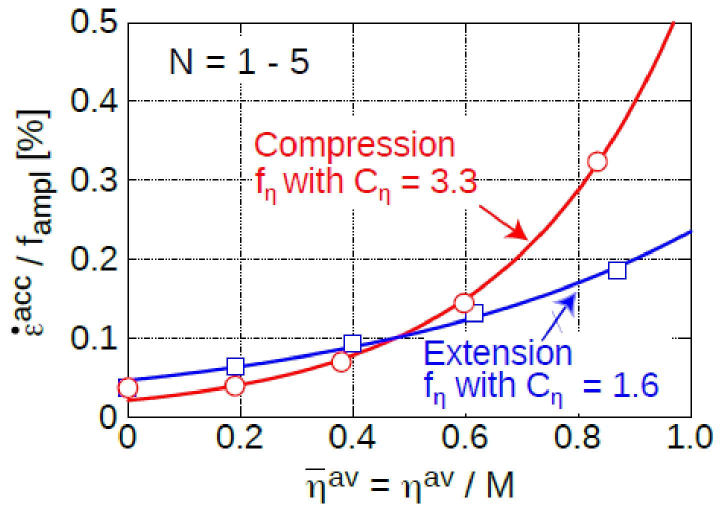
- HCA for clay (Staubach et al. 2021)
  - Intensity of accumulation:
    - Influence of the stress ratio

$$\dot{\boldsymbol{\sigma}} = \mathsf{E}:\left(\dot{\boldsymbol{\varepsilon}} - \dot{\boldsymbol{\varepsilon}}^{acc} - \dot{\boldsymbol{\varepsilon}}^{pl}\right) \text{ with } \dot{\sqcup} = \partial \sqcup / \partial N$$

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

$$\dot{\varepsilon}^{acc} = f_{ampl}\dot{f}_N f_e f_\eta f_{OCR} f_f$$

$$f_\eta = \exp(C_\eta \bar{\eta}^{av})$$



High cyclic accumulation (HCA) model

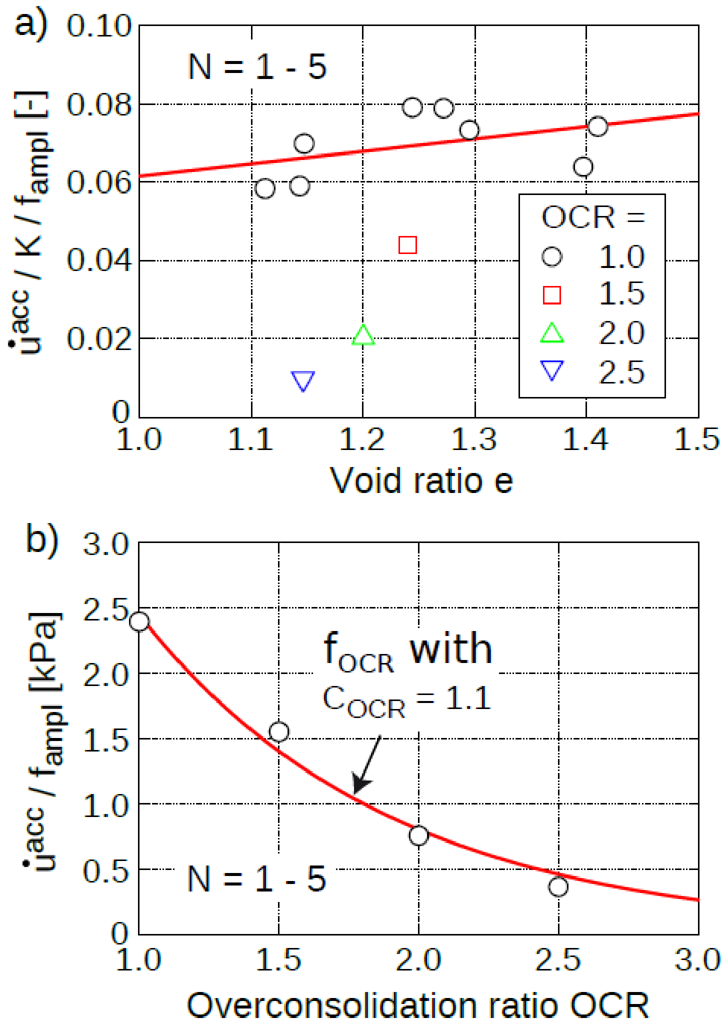
- HCA for clay (Staubach et al. 2021)
  - Intensity of accumulation:
    - Influence of the oveconsolidation ratio

$$\dot{\boldsymbol{\sigma}} = \mathrm{E}:\left(\dot{\boldsymbol{\varepsilon}} - \dot{\boldsymbol{\varepsilon}}^{acc} - \dot{\boldsymbol{\varepsilon}}^{pl}\right) \text{ with } \dot{\sqcup} = \partial \sqcup / \partial N$$

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

$$\dot{\varepsilon}^{acc} = f_{ampl}\dot{f}_N f_e f_\eta f_{OCR} f_f$$

$$f_{OCR} = \exp(-C_{OCR}(\mathrm{OCR}-1))$$



High cyclic accumulation (HCA) model

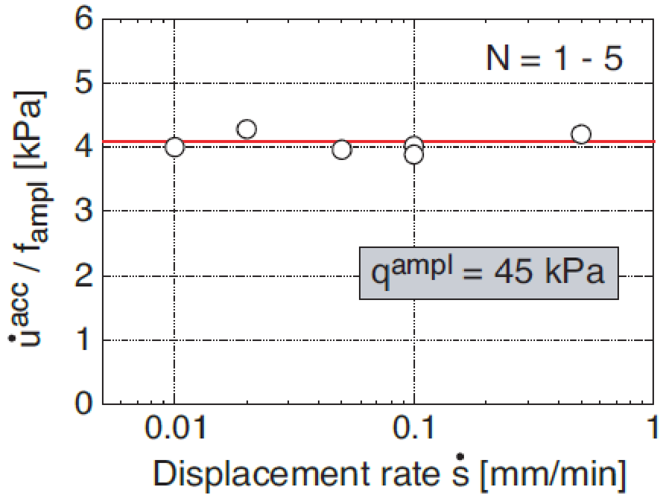
- HCA for clay (Staubach et al. 2021)
  - Intensity of accumulation:
    - Influence of the loading frequency

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

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

$\dot{\varepsilon}^{acc} = f_{ampl}\dot{f}_N f_e f_\eta f_{OCR} f_f$

$f_f = 1$ (Kaolin)



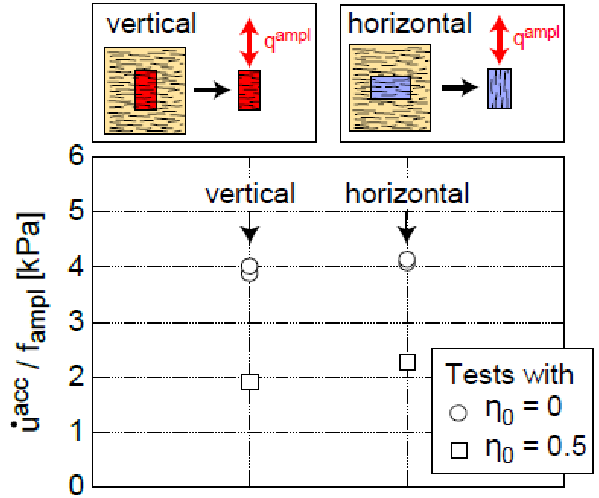
High cyclic accumulation (HCA) model

- HCA for clay (Staubach et al. 2021)
  - Intensity of accumulation:
    - Influence of the loading direction with respect to the sedimentation axis

$$\dot{\boldsymbol{\sigma}} = \mathrm{E}:\left(\dot{\boldsymbol{\varepsilon}} - \dot{\boldsymbol{\varepsilon}}^{acc} - \dot{\boldsymbol{\varepsilon}}^{pl}\right) \text{ with } \dot{\sqcup} = \partial \sqcup / \partial N$$

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

$$\dot{\varepsilon}^{acc} = f_{ampl}\dot{f}_N f_e f_\eta f_{OCR} f_f$$



High cyclic accumulation (HCA) model

- HCA for clay (Staubach et al. 2021)

  - Direction of accumulation:

$$\dot{\boldsymbol{\sigma}} = \mathsf{E} : \left(\dot{\boldsymbol{\varepsilon}} - \dot{\boldsymbol{\varepsilon}}^{acc} - \dot{\boldsymbol{\varepsilon}}^{pl}\right) \text{ with } \dot{\sqcup} = \partial \sqcup / \partial N$$

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

$$\mathbf{m} = \left[\frac{1}{3}\left(p^{av} - \frac{(q^{av})^2}{M^2 p^{av}}\right)\mathbf{1} + \frac{3}{M^2}(\boldsymbol{\sigma}^{av})^*\right]^{\rightarrow}$$

(similar to the MCC model approach)

High cyclic accumulation (HCA) model

- HCA for clay (Staubach et al. 2021)

  - Plastic strain

    - Associative flow rule

$$\dot{\boldsymbol{\sigma}} = \mathrm{E} : \left(\dot{\boldsymbol{\varepsilon}} - \dot{\boldsymbol{\varepsilon}}^{acc} - \dot{\boldsymbol{\varepsilon}}^{pl}\right) \text{ with } \dot{\sqcup} = \partial \sqcup / \partial N$$

$$\dot{\boldsymbol{\varepsilon}}^{pl} = \dot{\phi} \frac{\partial F}{\partial \boldsymbol{\sigma}} = \dot{\phi} \mathbf{m}$$

  - Hypoelastic stiffness

$$\dot{\boldsymbol{\sigma}} = \mathrm{E} : \left(\dot{\boldsymbol{\varepsilon}} - \dot{\boldsymbol{\varepsilon}}^{acc} - \dot{\boldsymbol{\varepsilon}}^{pl}\right) \text{ with } \dot{\sqcup} = \partial \sqcup / \partial N$$

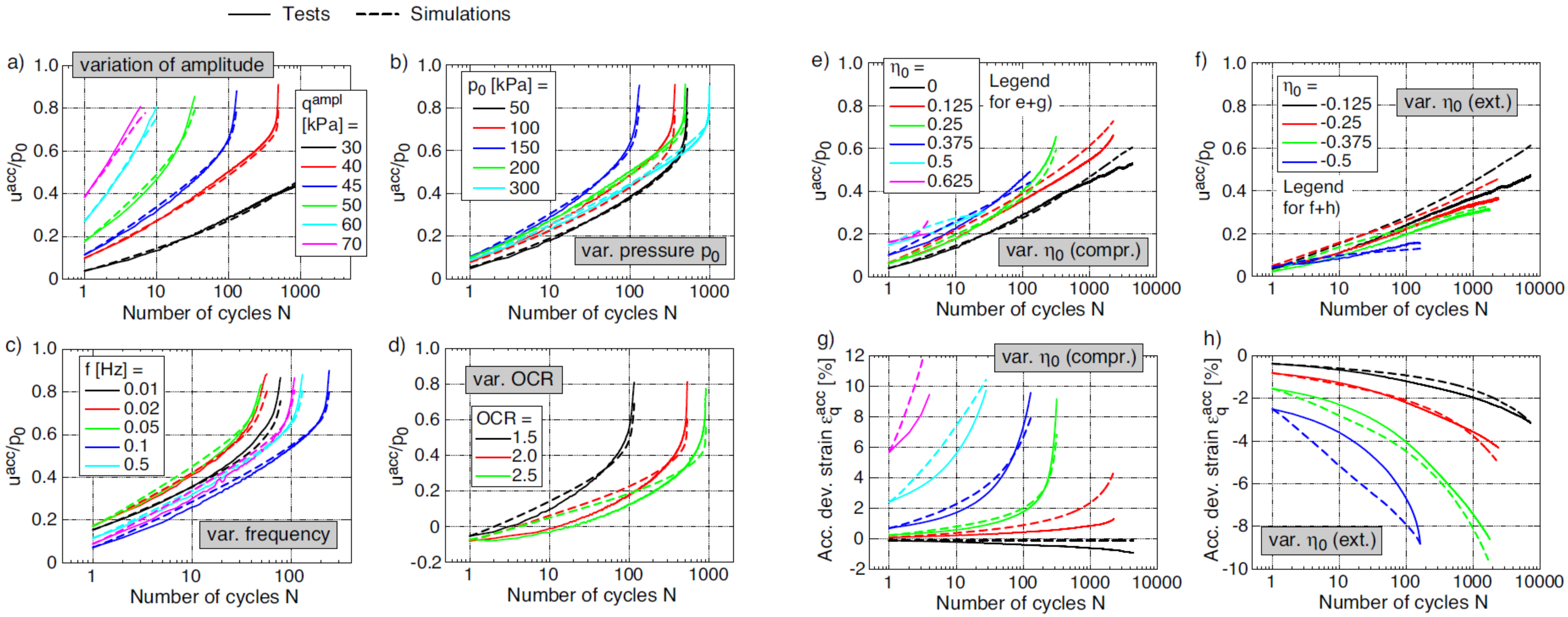
$$\mathrm{E} = \mathrm{K}\, \mathbf{1} \otimes \mathbf{1} + 2\mu\, \mathrm{I}$$

$$K = \frac{1+e}{\kappa} p, \qquad \mu = \frac{3K(1-2\nu)}{2(1+\nu)}$$

High cyclic accumulation (HCA) model

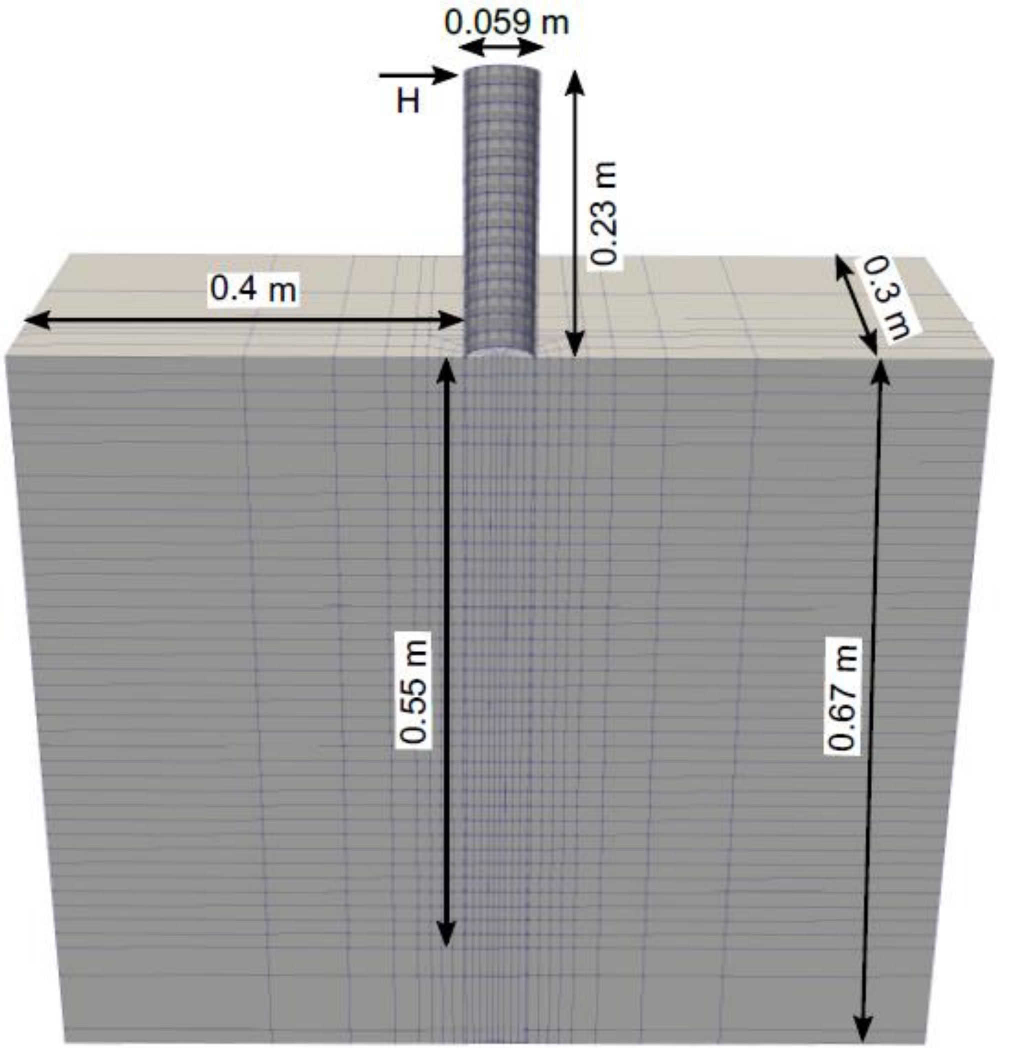
f_{OCR}	C_{ampl}	C_{N1}	C_{N2}	C_{N3}	C_e	C_η	C_{OCR}
OCR_0	0.6	0.00115	0.8	0.0	-0.97	2.9	0.5
OCR	0.8	0.00125	0.5				

- HCA for clay (Staubach et al. 2021)
  - Element tests of Kaolin



Back-analysis of centrifuge tests on monopiles in soft clay

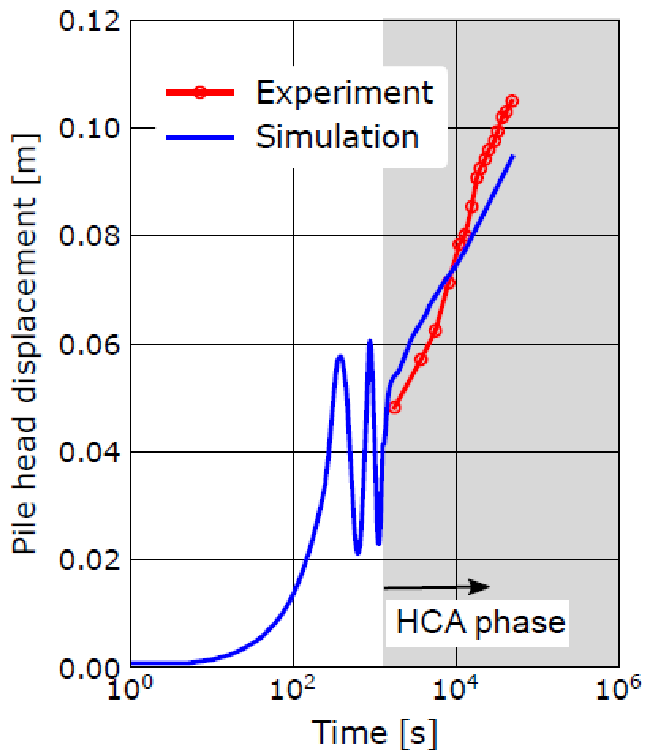
- Finite Element model with numgeo (Staubach et al. 2021)

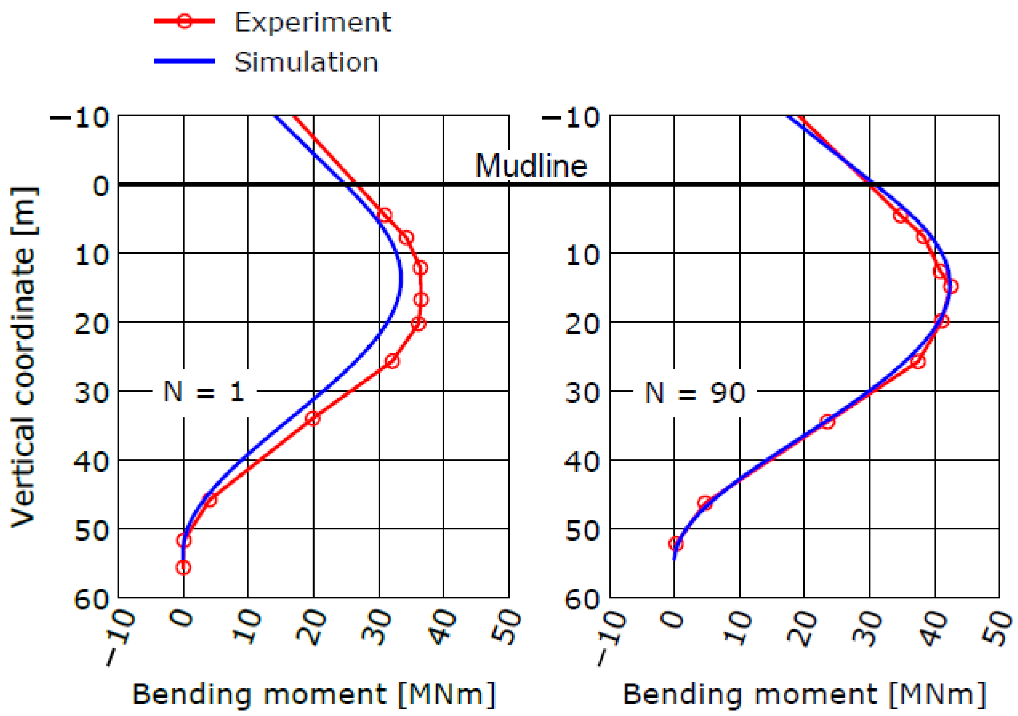


  - Application of the self-weight of the soil and pile at 1 g
  - Application of increased gravity to 100 g by the centrifuge
  - Application of the average value of the lateral force $H_{av} = 62.5\ \mathrm{N}$
  - Calculation of the first cycle, using the AVISA model
  - The average load H_{av} was superposed by a sinusoidal cyclic load with the amplitude $H_{ampl} = 37.5\ \mathrm{N}$
  - Calculation of the second cycle, using the AVISA model.
  - Calculation of permanent deformations due to N = 100 further cycles using the HCA model.

Back-analysis of centrifuge tests on monopiles in soft clay

- Finite Element simulation with numgeo (Staubach et al. 2021)

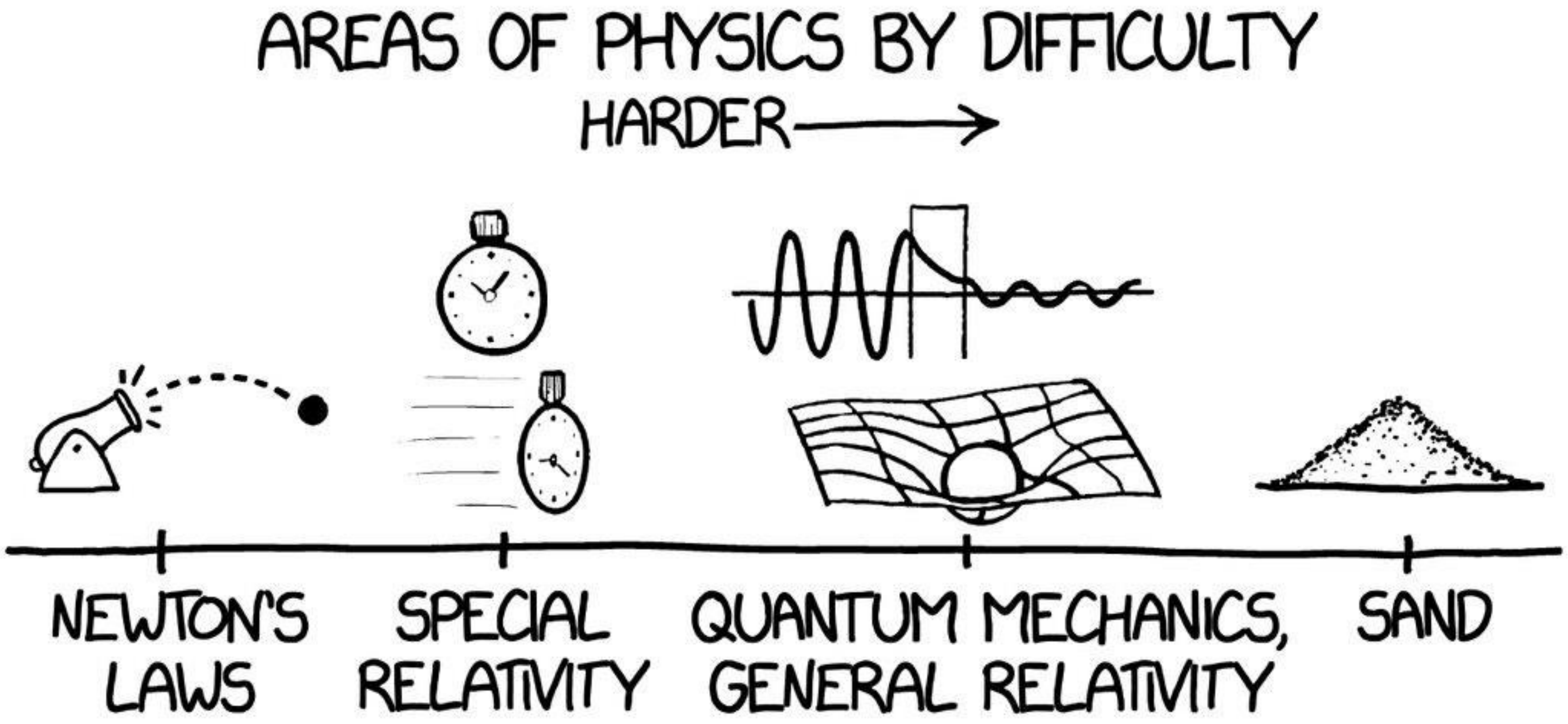




Summary and Conclusions

- Experimental investigations
- Explicite constitutive models
- Implicite constitutive models
- Calibration and verification

Function	Material constant	Ref. quant.
$f_{\text{ampl}} = \left(\varepsilon^{\text{ampl}}/\varepsilon^{\text{ampl}}_{\text{ref}}\right)^{C_{\text{ampl}}}$	C_{ampl}	$\varepsilon^{\text{ampl}}_{\text{ref}}$
$\dot{f}_N = \frac{C_{N1}C_{N2}}{1+C_{N2}N} + C_{N1}C_{N3}$	C_{N1}, C_{N2}, C_{N3}	
$f_e = \frac{(C_e-e)^2}{1+e} \frac{1+e_{\text{ref}}}{(C_e-e_{\text{ref}})^2}$	C_e	e_{ref}
$f_\eta = \exp\left(C_\eta \, \|\eta^{\text{av}}\|/M\right)$	C_η	
$f_{OCR} = \exp[-C_{\text{OCR}}(OCR - 1.0)]$	C_{OCR}	
$f_f = 1$	-	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SPECIAL RELATIVITY
QUANTUM MECHANICS, GENERAL RELATIVITY
SAND

Thank You!