Investigations of soil behavior using triaxial testing techniques

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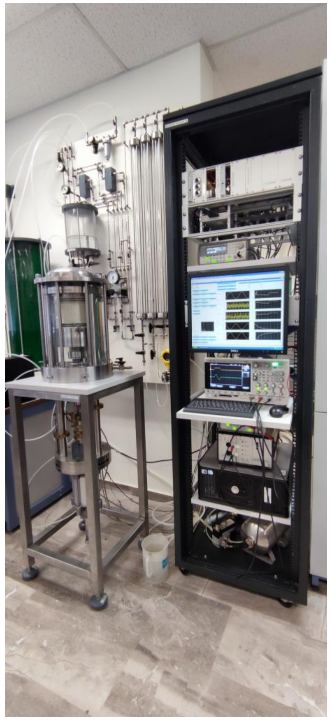
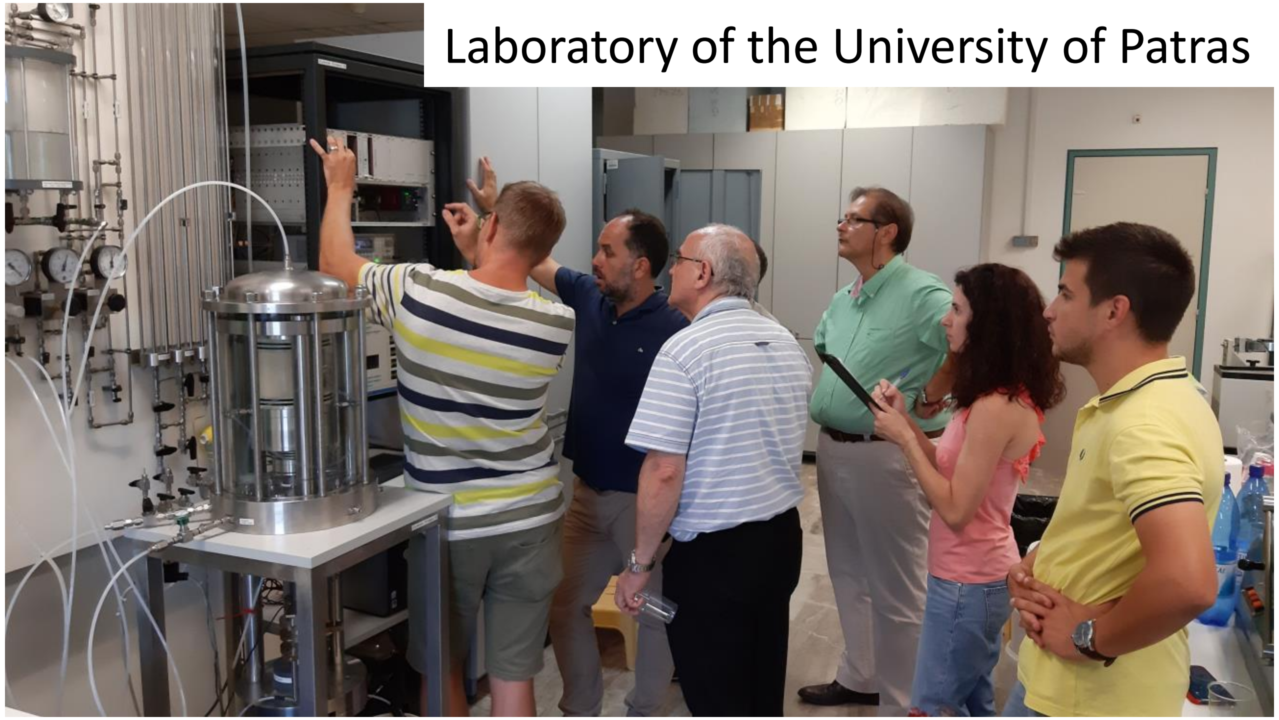




Laboratory of the University of Patras

Geotechnical issues

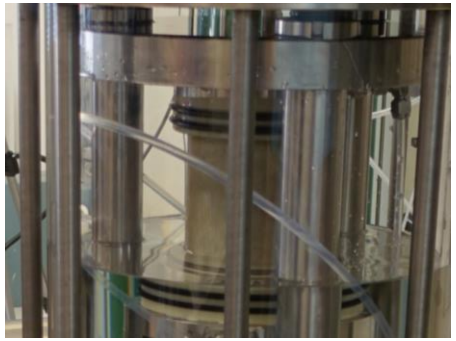
- Coarse-grained soils under drained monotonic loading
  → Shear parameters (friction angle) for verifications: Slope stability, bearing capacity, sliding, earth pressure calculation
- Coarse-grained soils under undrained monotonic loading
  → Flow liquefaction of slopes or opencast mines (as a result of flooding after mining)

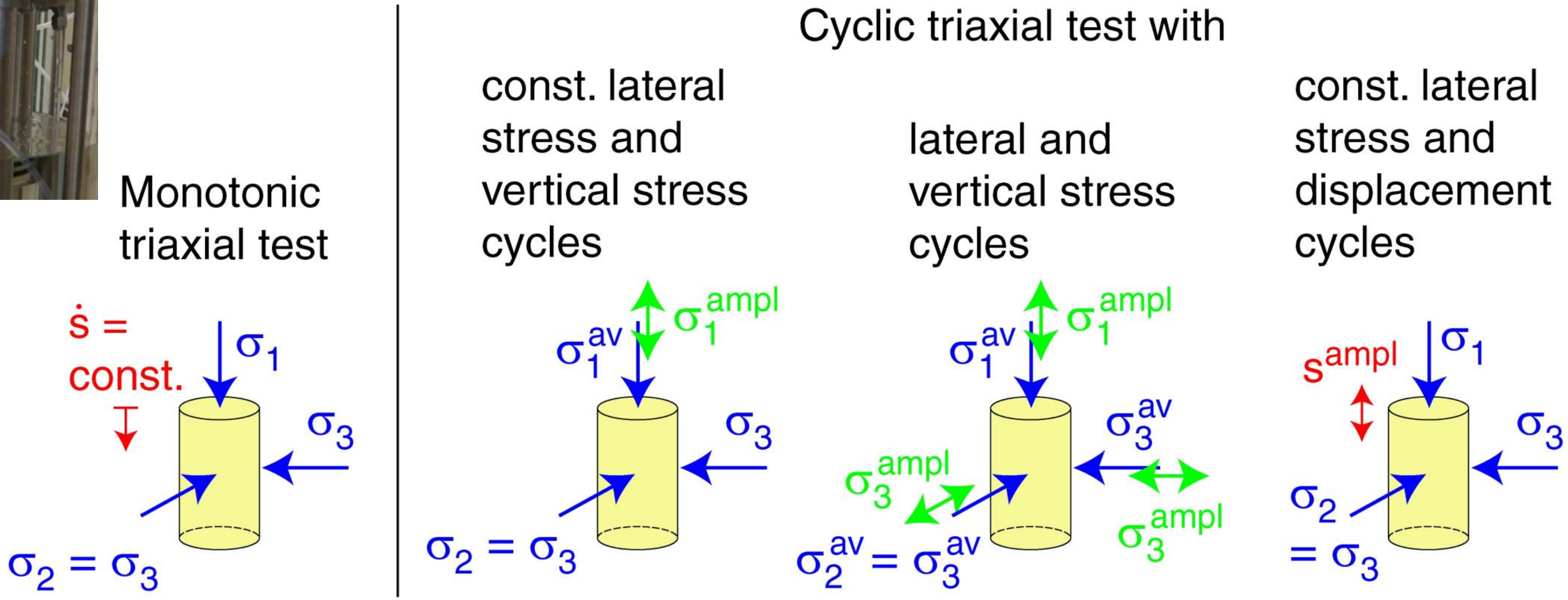
- Coarse-grained soils under drained cyclic loading
  → Offshore-Windparks
  → High-speed rail lines

- Coarse-grained soils under undrained cyclic loading
  → Soil liquifaction after earthquake

- Fine-grained soils under drained monotonic loading
  → Shear strength parameters (friction angle, cohesion)
- Fine-grained soils under undrained monotonic loading
  → Offshore-Windparks, oil rigs

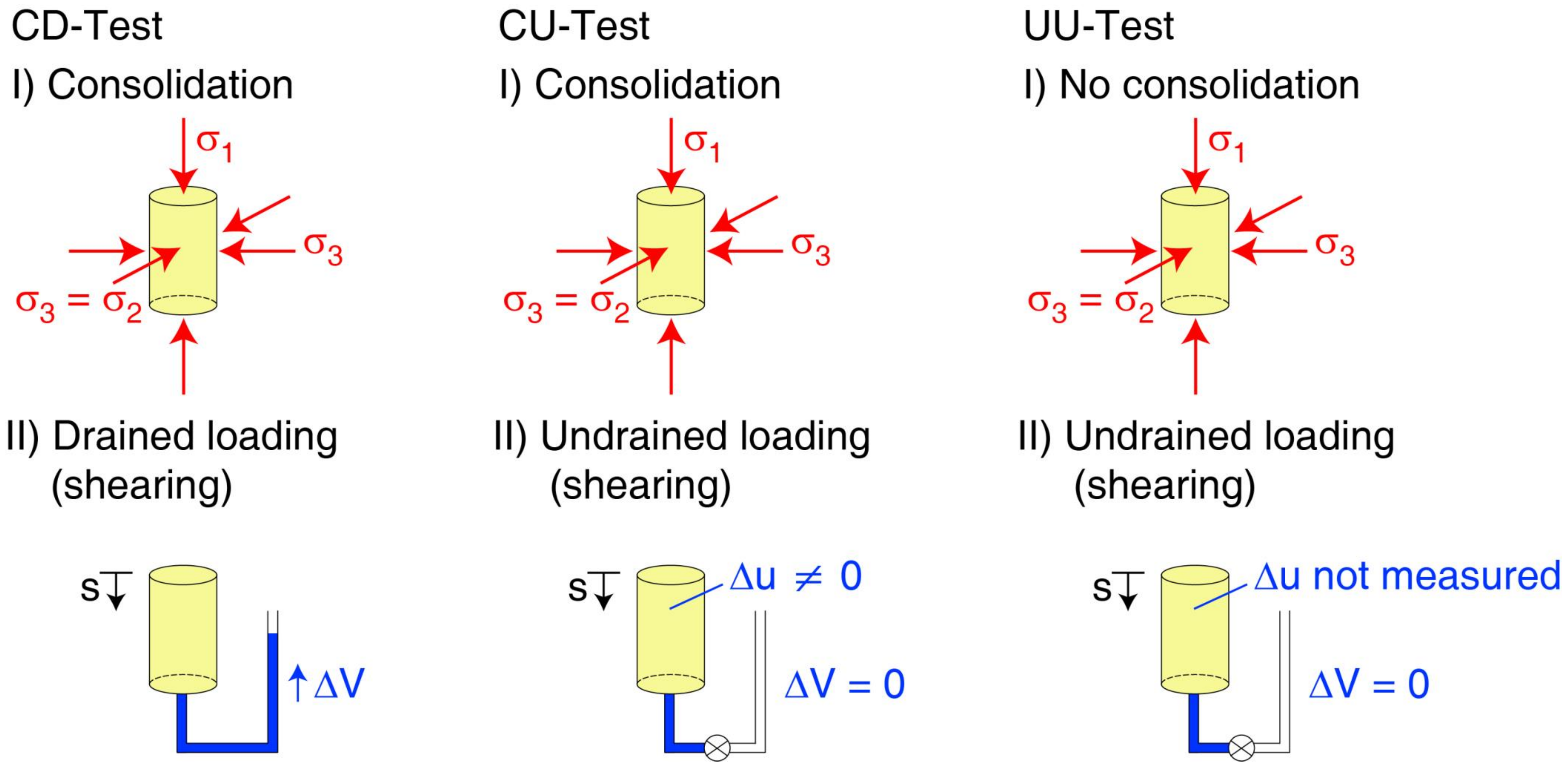
Types of triaxial tests – loading



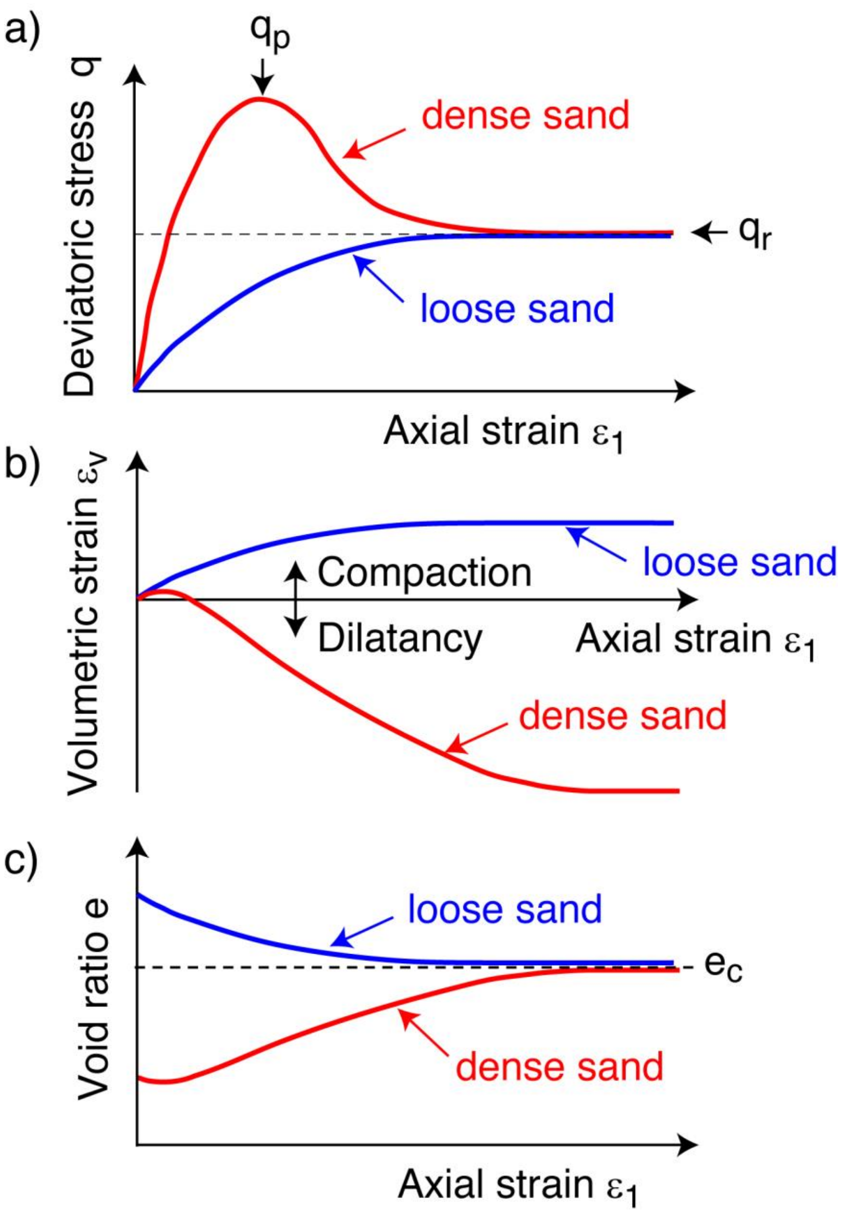


Amplitude: $\cup^{ampl}$
Average: $\cup^{av}$

Types of triaxial tests – consolidation and drainage

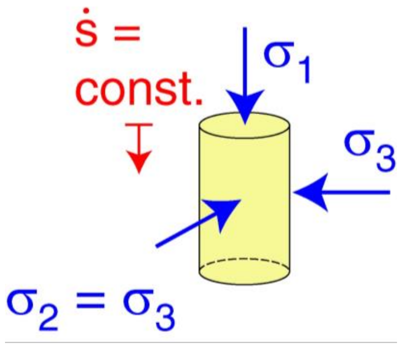


CD – Triaxial test results

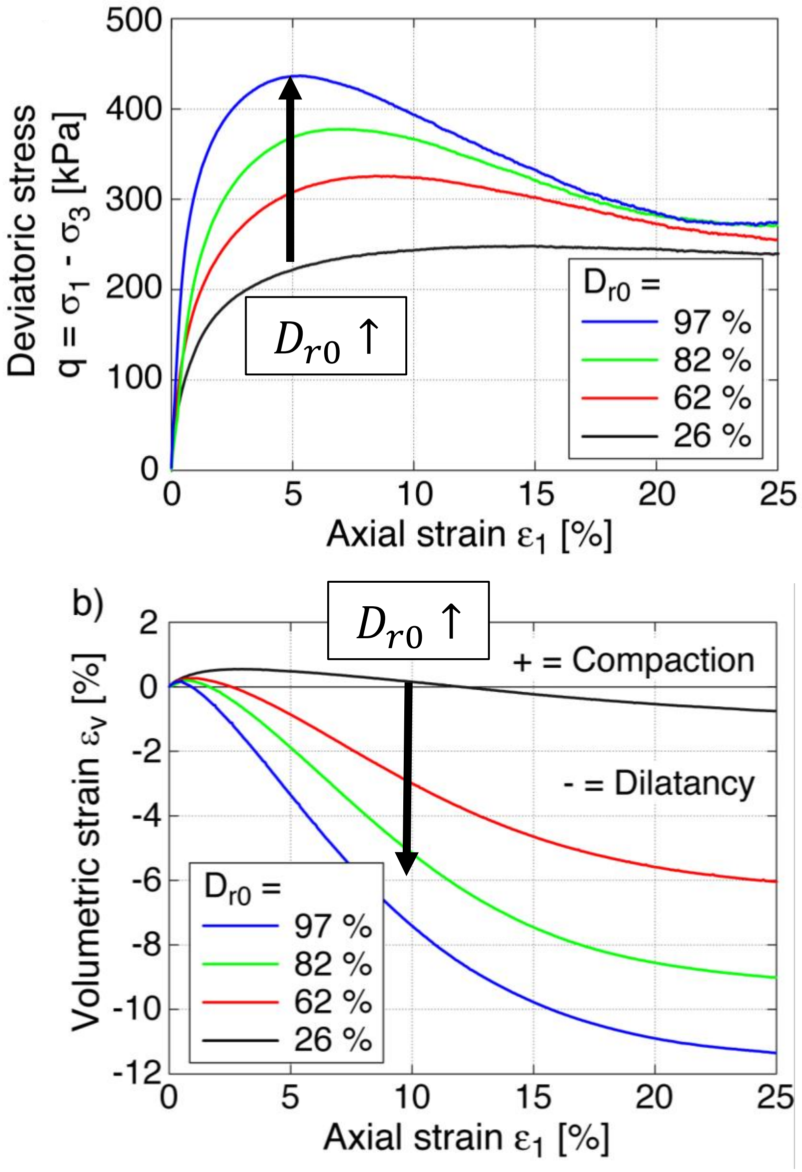


Typical results for Karlsruhe sand:

- $\sigma_1 = \sigma_3 = 600$ kPa and $u = 500$ kPa
- $\dot{s} = 0{,}1$ mm/min

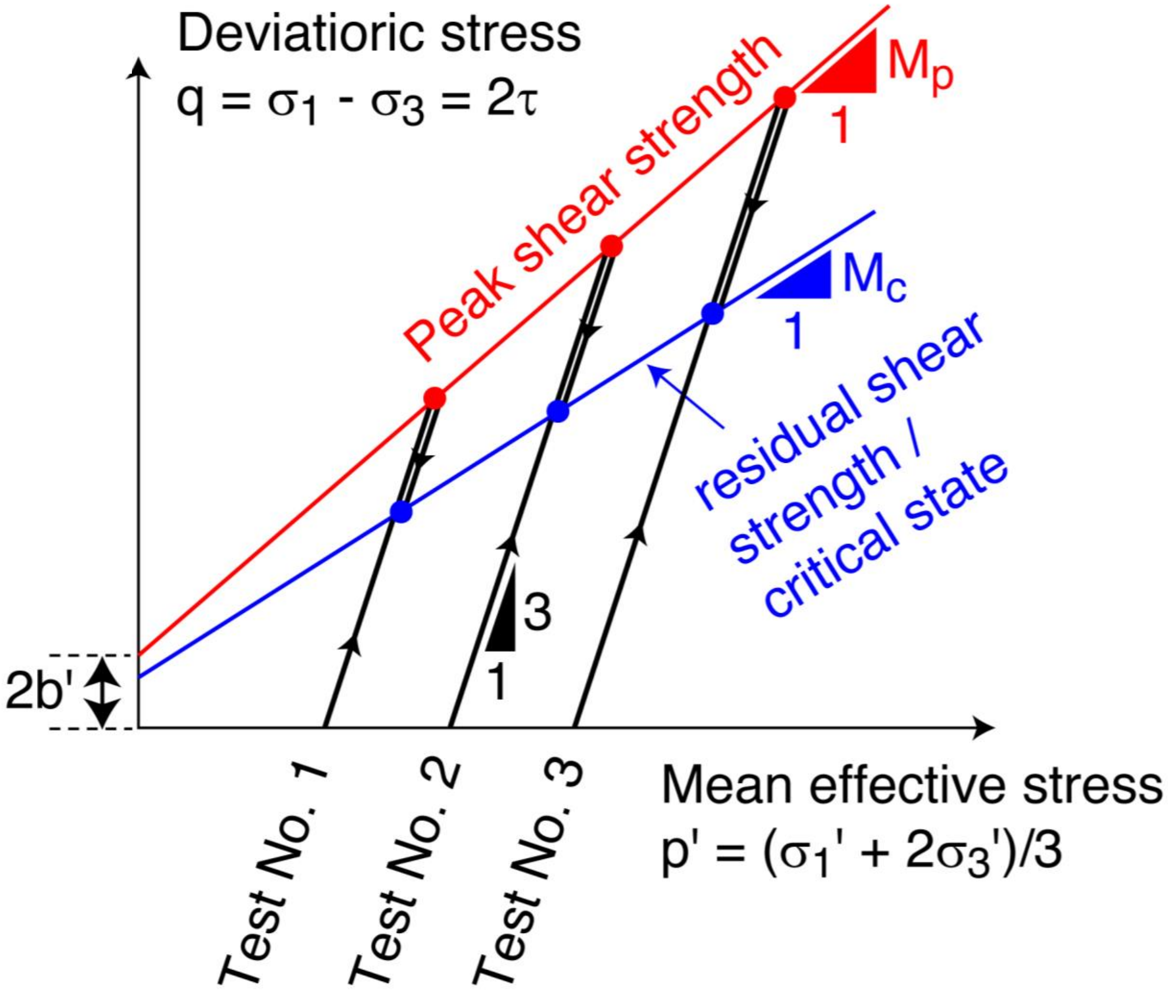


- Variation of the relative density D_{r0}



CD – Triaxial test results

Effective stress paths for sand



Effective stresses: $\sigma_1' = \sigma_1 - u$, $\sigma_3' = \sigma_3 - u$

Mean pressure: $p' = 1/3\,(\sigma_1' + 2\sigma_3')$

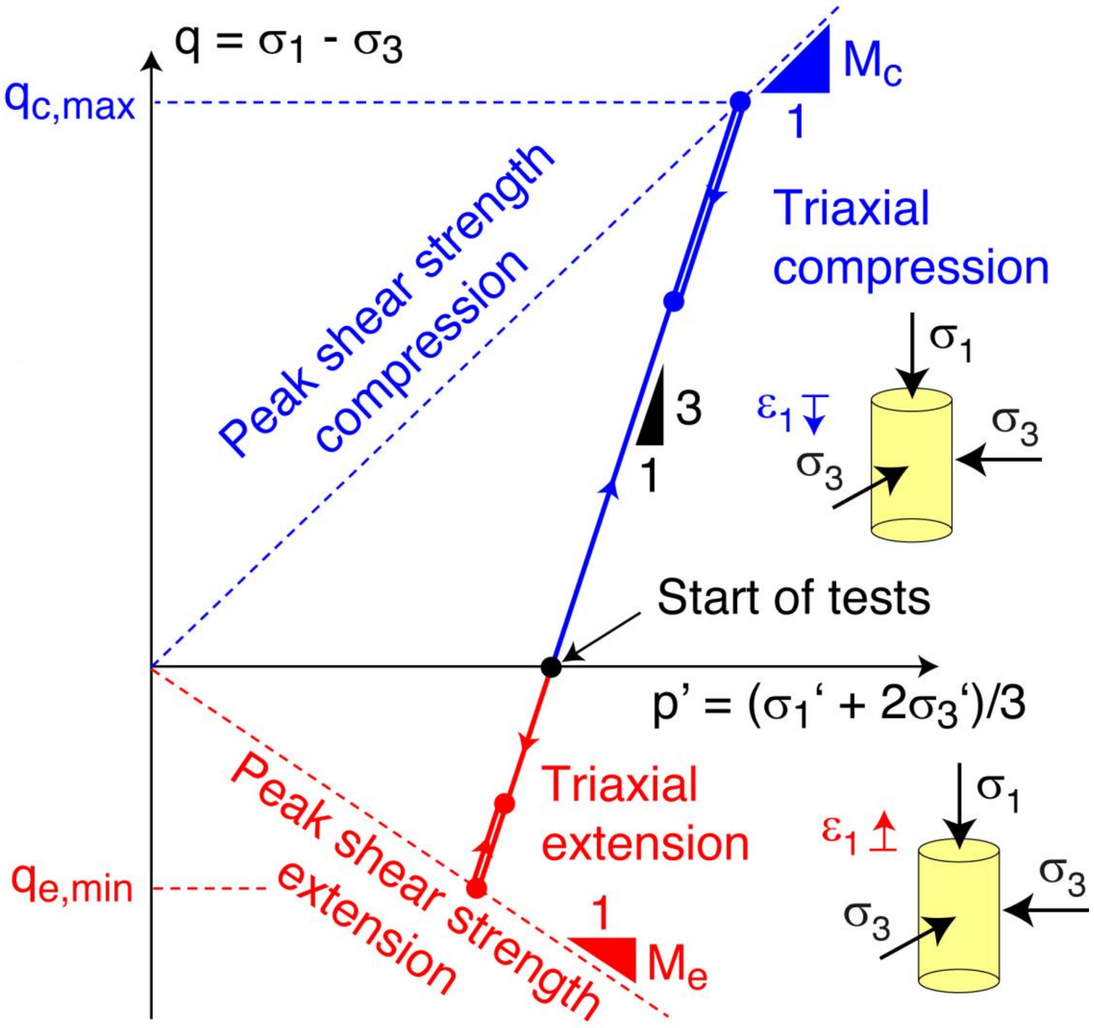
Deviatoric stress: $q = \sigma_1' - \sigma_3' = \sigma_1 - \sigma_3$

Stress ratios: $M_{\cup} = \frac{6 \cdot \sin(\varphi)}{3 - \sin(\varphi)}$

Friction angle: $\varphi = \arcsin\left(\frac{3M}{6+M}\right)$

CD – Triaxial test results

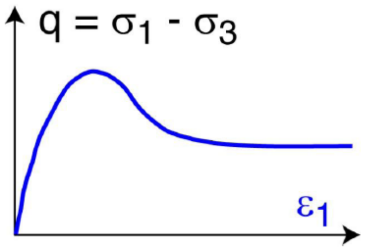
Effective stress paths for sand



Compression:

$$M_c = \frac{6 \cdot \sin(\varphi)}{3 - \sin(\varphi)}$$

$$\varphi = \arcsin\left(\frac{3M_c}{6 + M_c}\right)$$

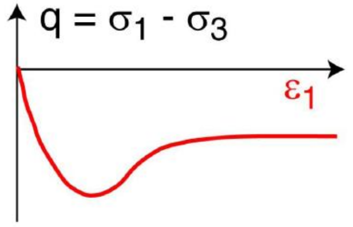


E.g. acting earth pressure on OWA foundation

Extension:

$$M_e = \frac{6 \cdot \sin(\varphi)}{3 + \sin(\varphi)}$$

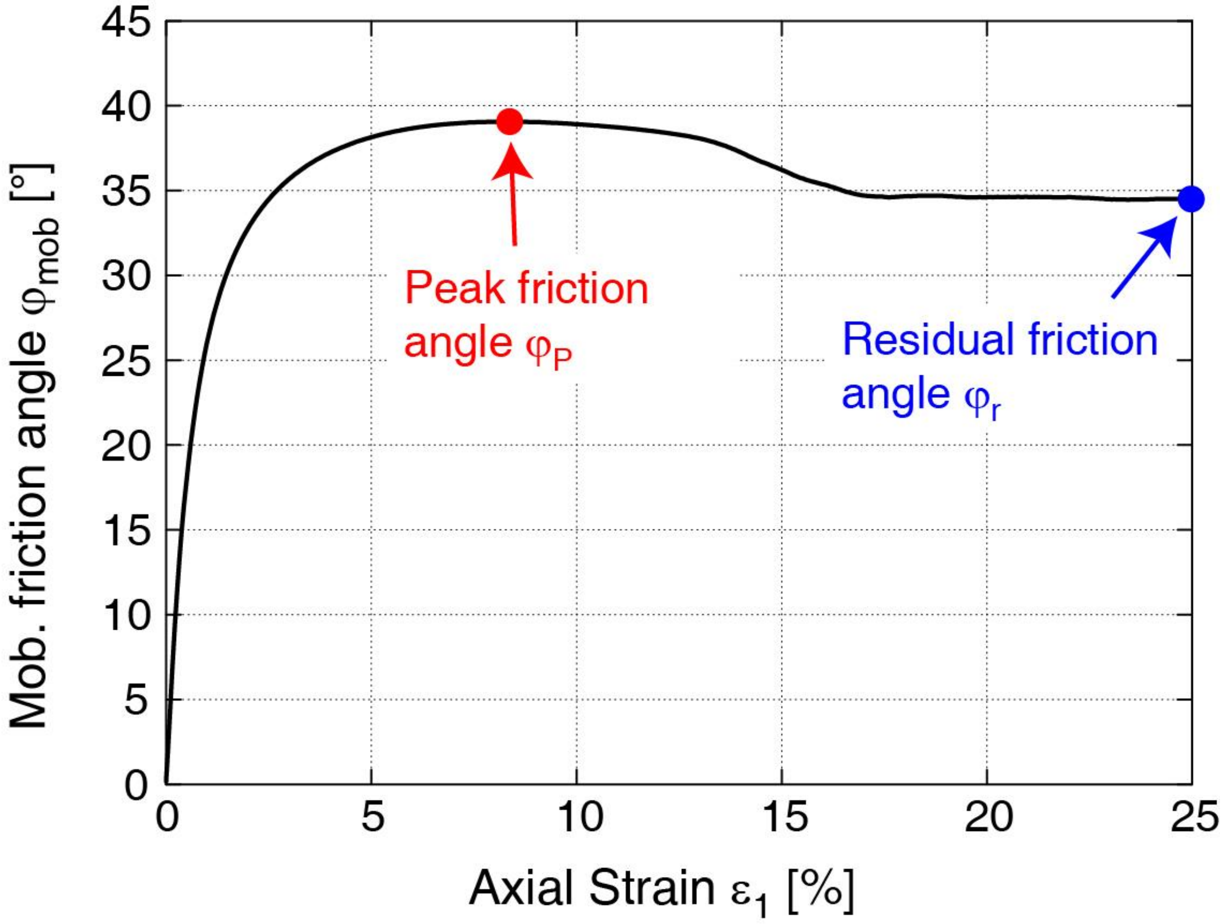
$$\varphi = \arcsin\left(\frac{-3M_e}{6 + M_e}\right)$$



E.g. acting buoyancy on an underwater concrete base

CD – Triaxial test results

Determination of the friction angle



Karlsruhe sand

Shear parameters:

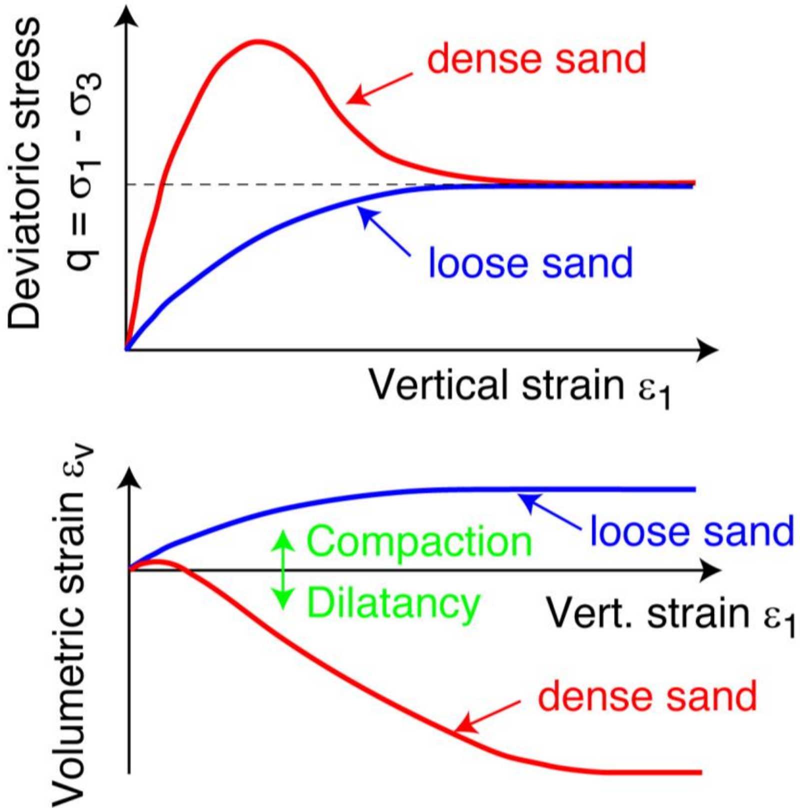
Peak friction angle φ_P at the maximum

Residual friction angle $\varphi_r = \varphi_c$ after large shear strain

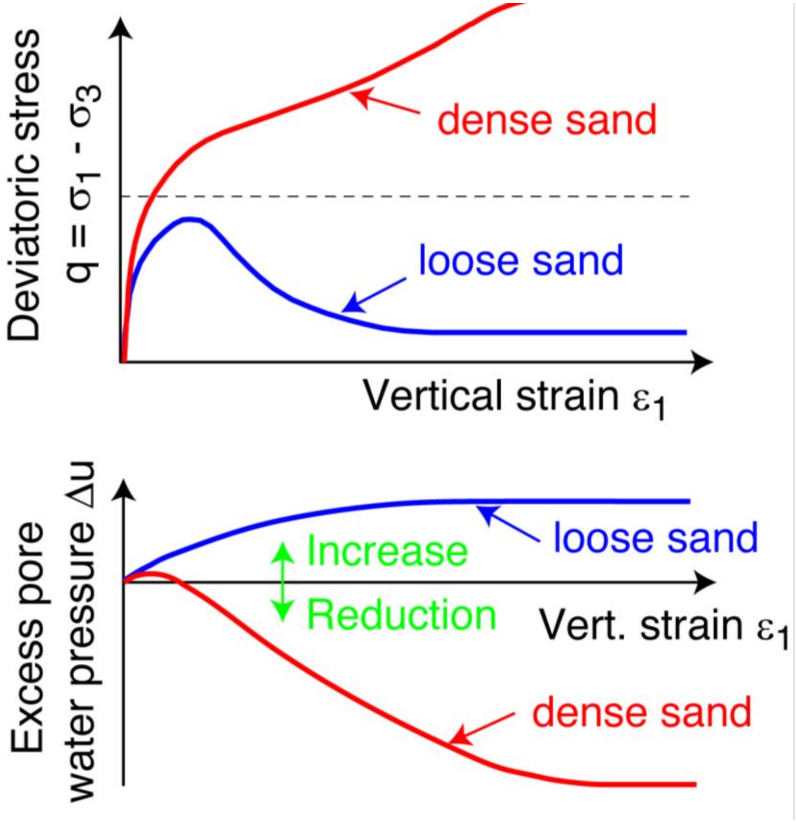
CD- vs. CU - Triaxial test

Schematic comparison of the experiments

Drained tests: $\Delta u = 0$

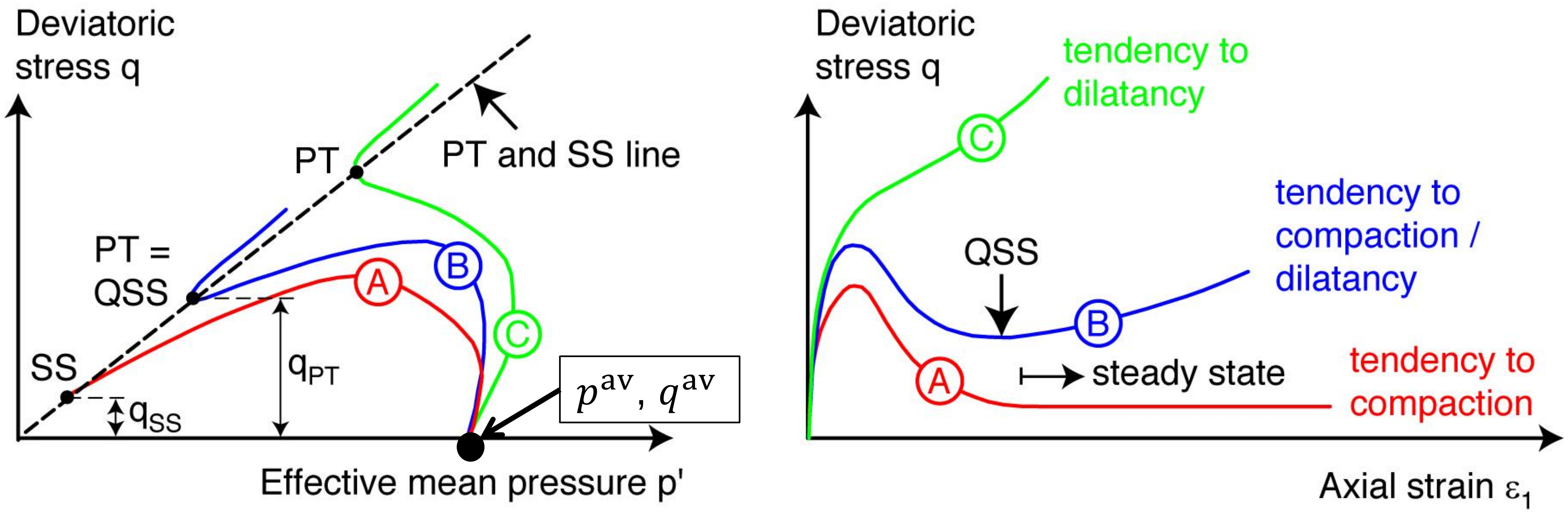


Undrained tests: $\varepsilon_v = 0$



CU - Triaxial test

Influence of the void ratio

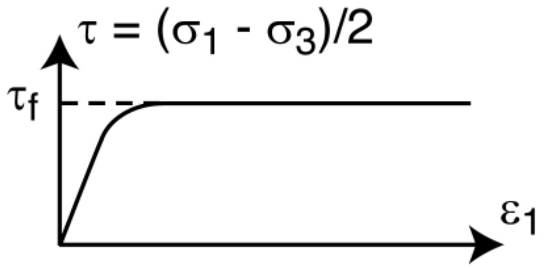


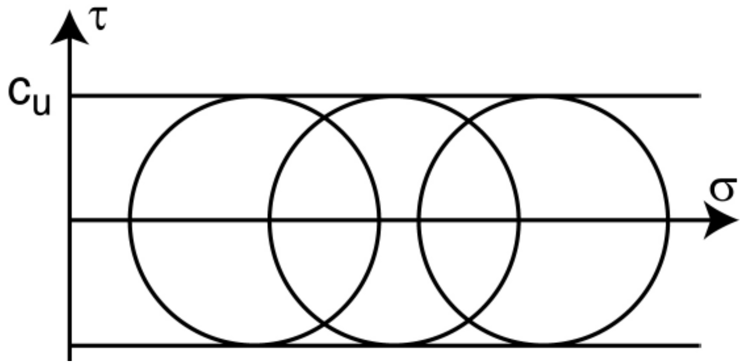
A = loose sand, purely contractive behavior, q rises first and then falls to q_{SS}, finally reaches the „steady-state" (SS)

B = medium dense sand, initially contractant behavior, q first increases, then temporarily decreases to $q_{QSS} = q_{PT}$ and finally increases again after passing through the „quasi-steady state" (QSS) dilatant behavior so-called „phase transformation" (PT)

C = dense sand, q increases continuously

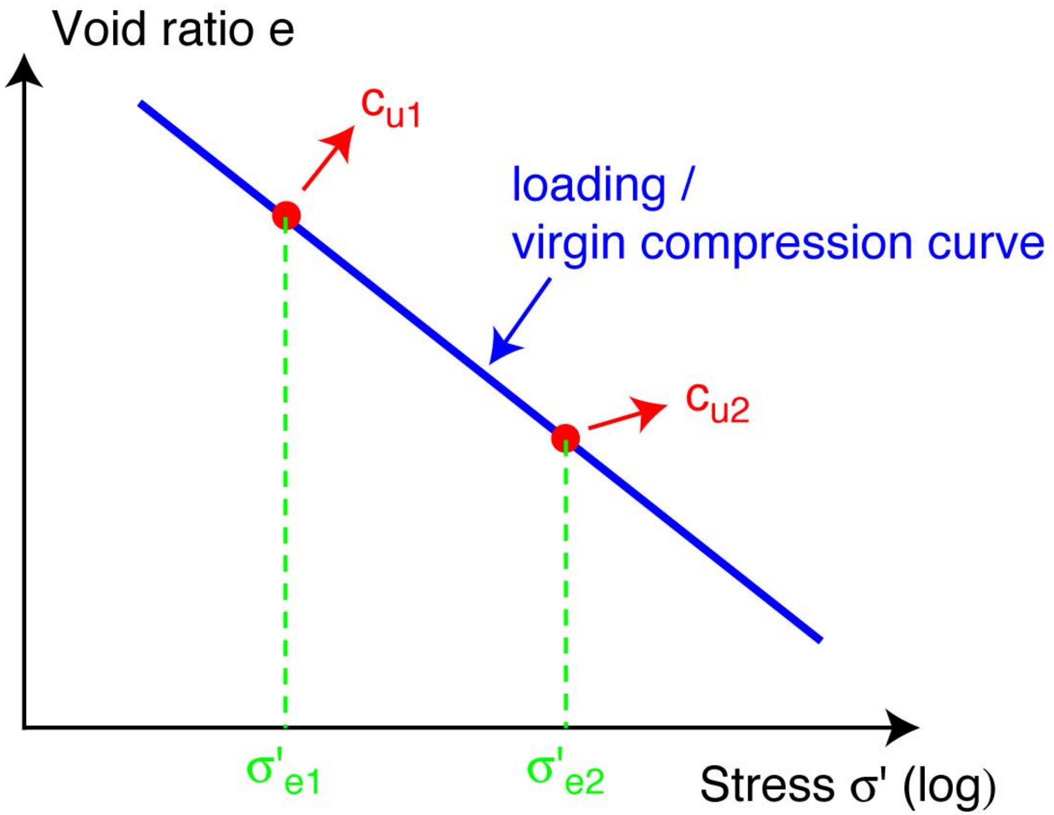
UU - Triaxial test





- Typical trend of shear stress τ with increasing vertical strain ε_1 of a normally consolidated clay specimen.
- Initial increase in τ with ε_1 → τ_f = const.
- Performance of 3 UU triaxial tests
- Varying the total lateral stress σ_3
- From each test, determine the maximum total axial stress $\sigma_{1,\max}$ achieved at large strains
- Mohr circles with total normal stress σ
  → due to complete water saturation → the same radius
  → horizontal tangent to circles → axis intercept = c_u
- Fully saturated: $\varphi_u = 0$ or partially saturated samples $\varphi_u > 0$

UU - Monotonic triaxial test



- Undrained cohesion c_u is proportional to equivalent stress σ_e'
- Normal consolidated soil: $\sigma_e' = \sigma'$
- If c_{u1} at σ_{e1}' is known, c_{u2} at σ_{e2}' can be estimated using

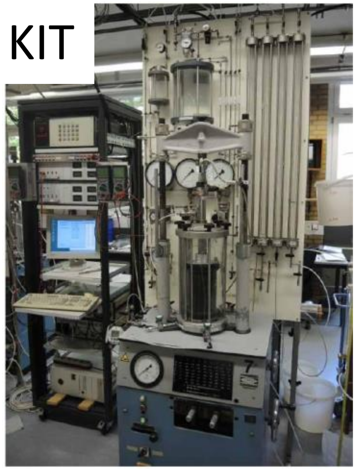
$$\frac{c_{u2}}{c_{u1}} = \frac{\sigma_{e2}'}{\sigma_{e1}'}$$

- Increase of equivalent stress σ_e' by certain factor → increase of c_u i.e. c_u is stress-dependent

Two stress states on the initial stress curve in the e-σ-Diagram with the equivalent stresses σ_{e1}' and σ_{e1}' and the corresponding values of undrained cohesion c_{u1} and c_{u2}

Type 1: Triaxial devices for monotonic tests

KIT



Control variables:

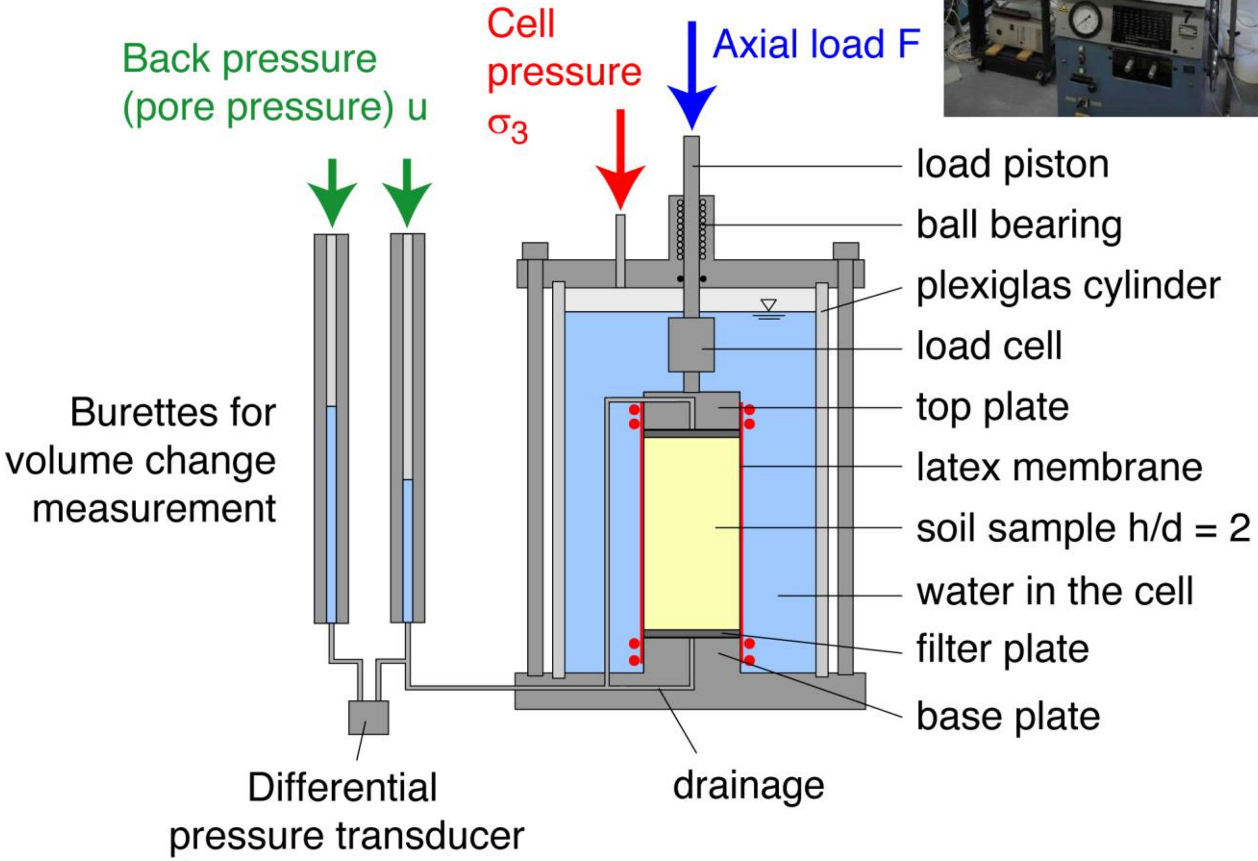
- Vertical force F (load cell) → vertical stress σ_1
- Const. lateral stress σ_3 (cell pressure transducer)
- Pore water pressure u (pore water transducer)
- Displacement rate $\dot{s}$ (servomotor)

Measurements:

- Change of sample height Δh (displacement transducer)
- Volume change ΔV (differential pressure transducer)

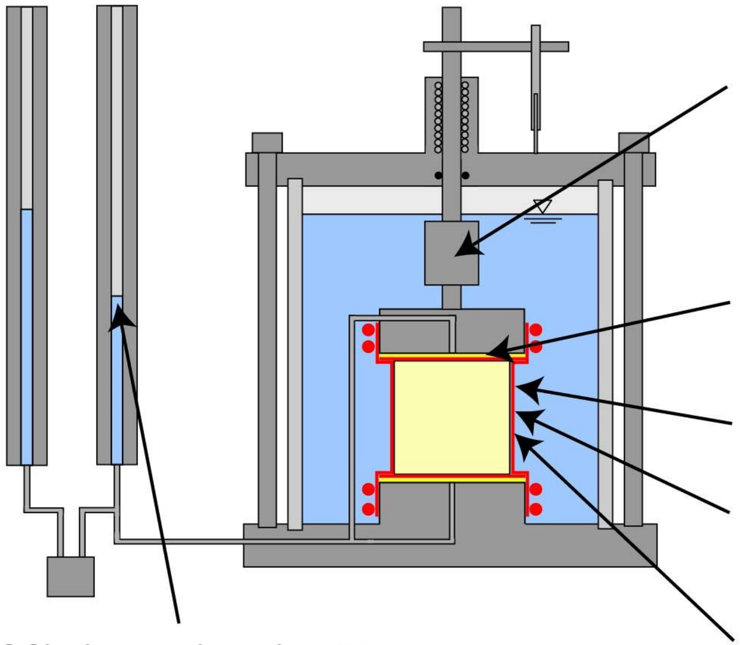
Calculation variables:

- Vertical strain $\varepsilon_1 = \Delta h / h_0$
- Volumetric strain $\varepsilon_v = \Delta V / V_0$
- Lateral strain $\varepsilon_3 = (\varepsilon_v - \varepsilon_1)/2$



Comments on the evaluation

Sources of error



Inaccuracies in the displacement measurement due to deformation of the system (e.g. load cell)

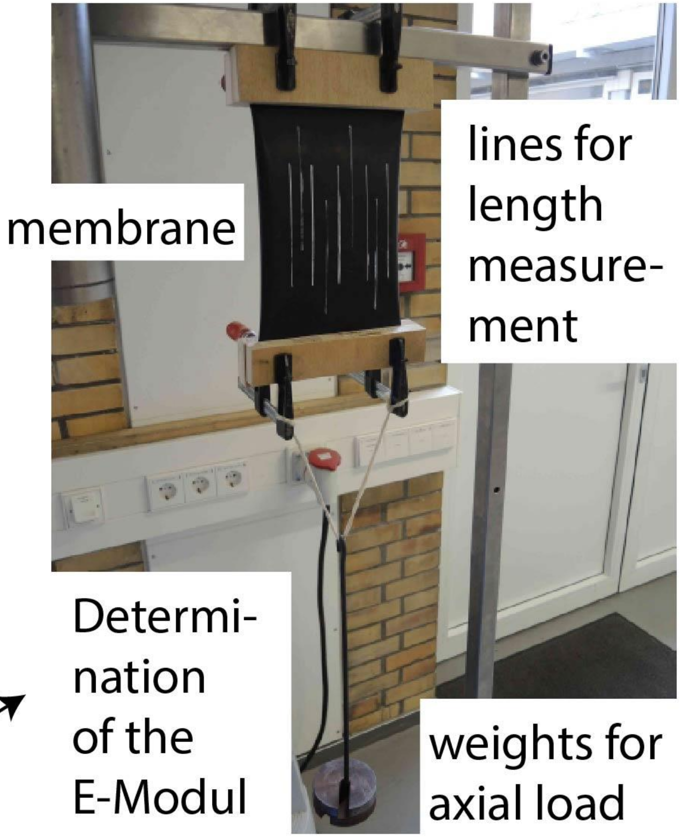
Inaccuracies in the displacement measurement due to deformation of the rubber plate and squeezing out of the grease layer

Membrane penetration

Diffusion of water in long-term tests

Membrane absorbs force (especially during extension)

Miniscus in pipette, evaporation from pipette



Type 2: Triaxial devices for a small number of slow cycles ($f < 0.01$ Hz)

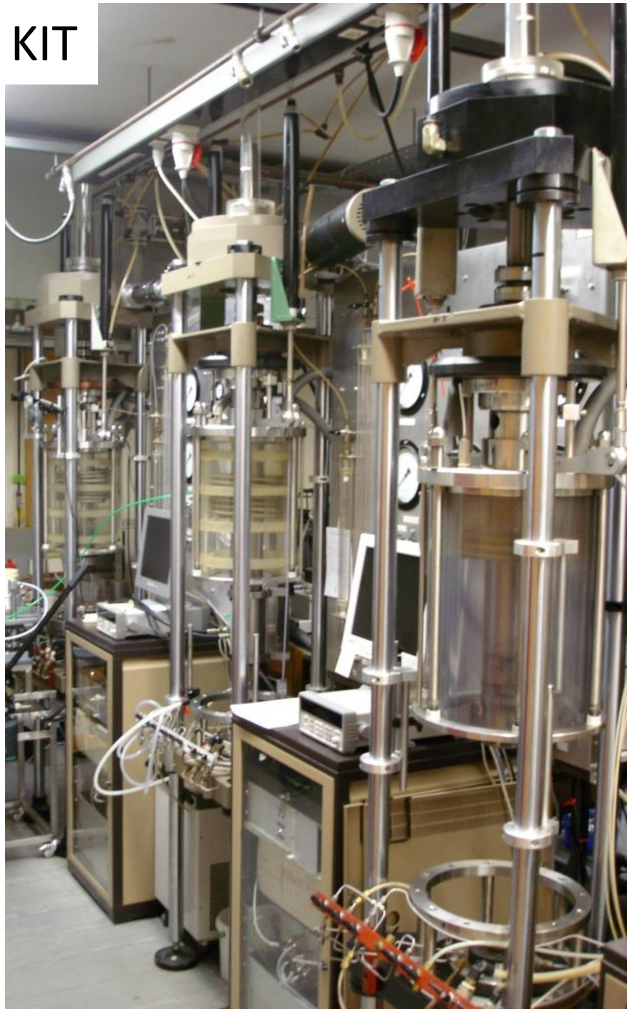
Control variables:

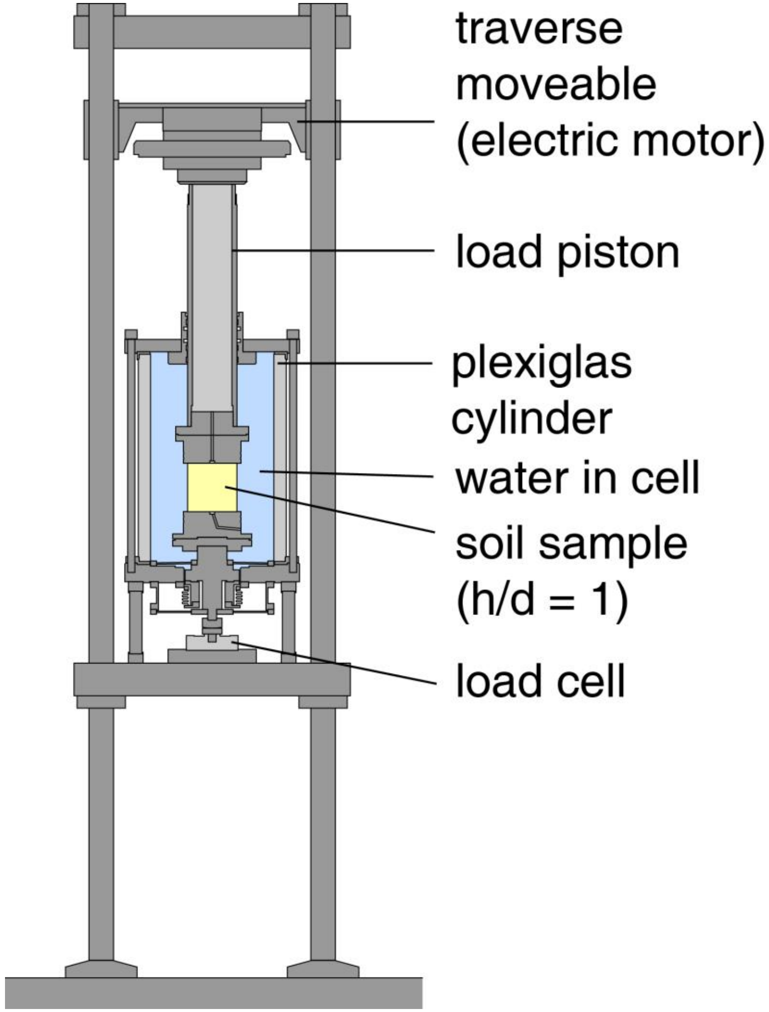
- Vertical force F^{ampl} (load cell)
  → vertical stress cycles σ_1^{ampl}
- Const. lateral stress σ_3
  (cell pressure transducer)
- Pore water pressure u
  (pore water transducer)
- Displacement rate $\dot{s}$ (electric motor)

Measurements:

- Change of sample height Δh
  (Displacement transducer)
- Volume change ΔV
  (differential pressure transducer)

Calculation variables: see Type 1





Type 3: Triaxial devices for a large number of fast cycles (f < 2 Hz)

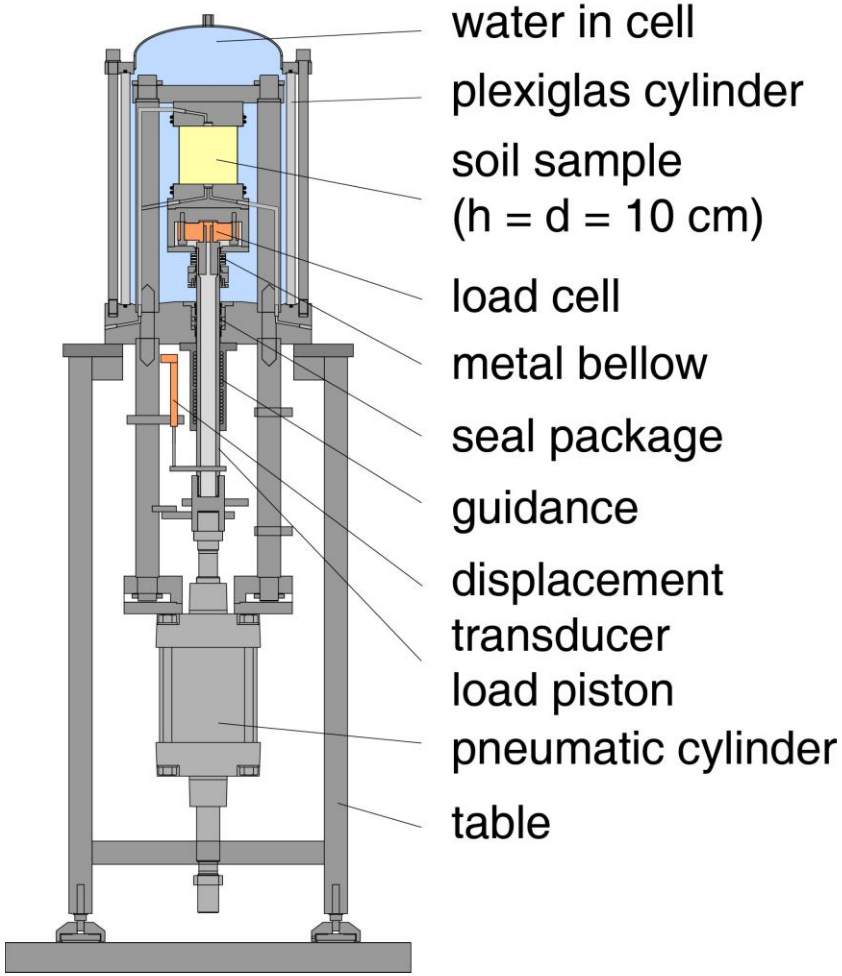
Control variables:

- Vertical force F^{ampl} (load cell)
  → vertical stress cycles σ_1^{ampl}
- Lateral stress cycles σ_3^{ampl} (cell pressure transducer)
- Pore water pressure u (pore water transducer)

Measurands:

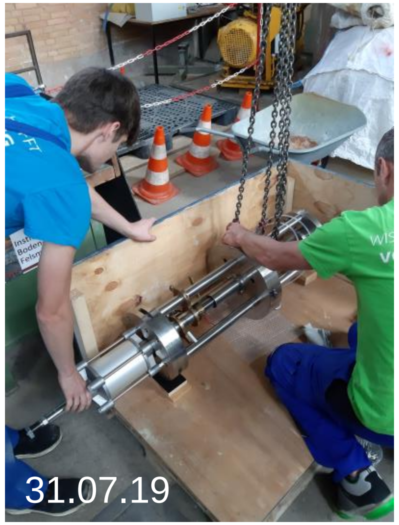
- Change of sample height Δh (Displacement transducer)
- Volume change ΔV (differential pressure transducer)

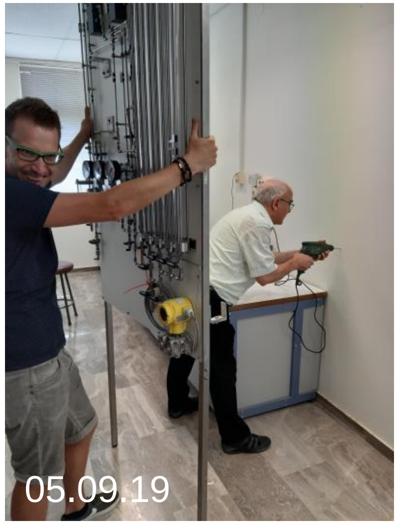
Calculation variables: see Type 1



Type 3: Triaxial devices for a large number of fast cycles (f < 2 Hz)

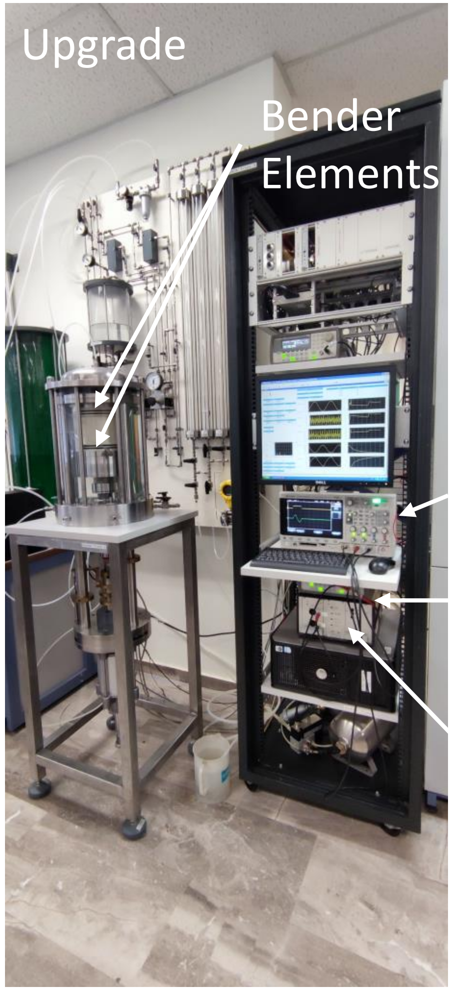
Transport from KIT to the University of Patras in September 2019



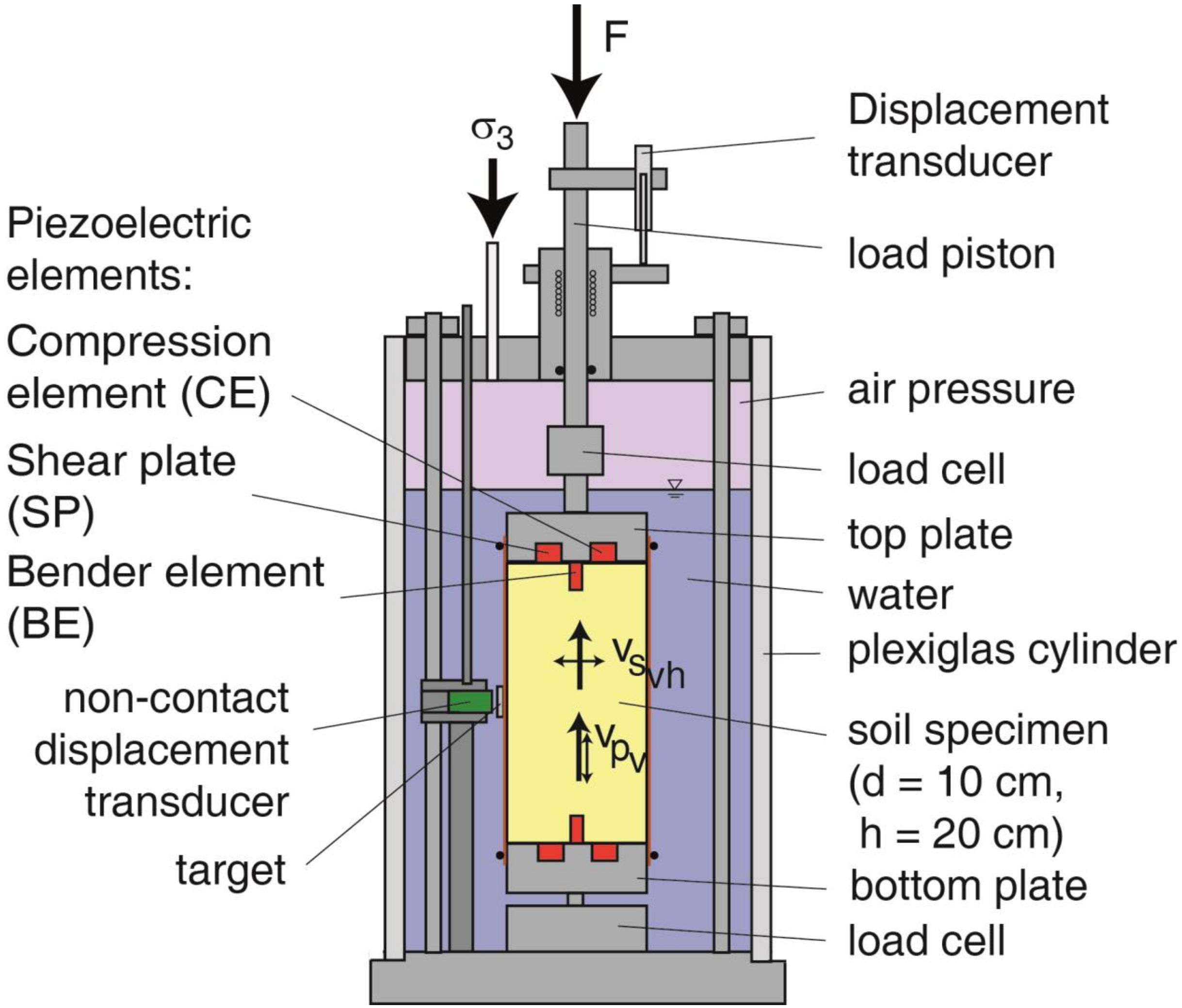


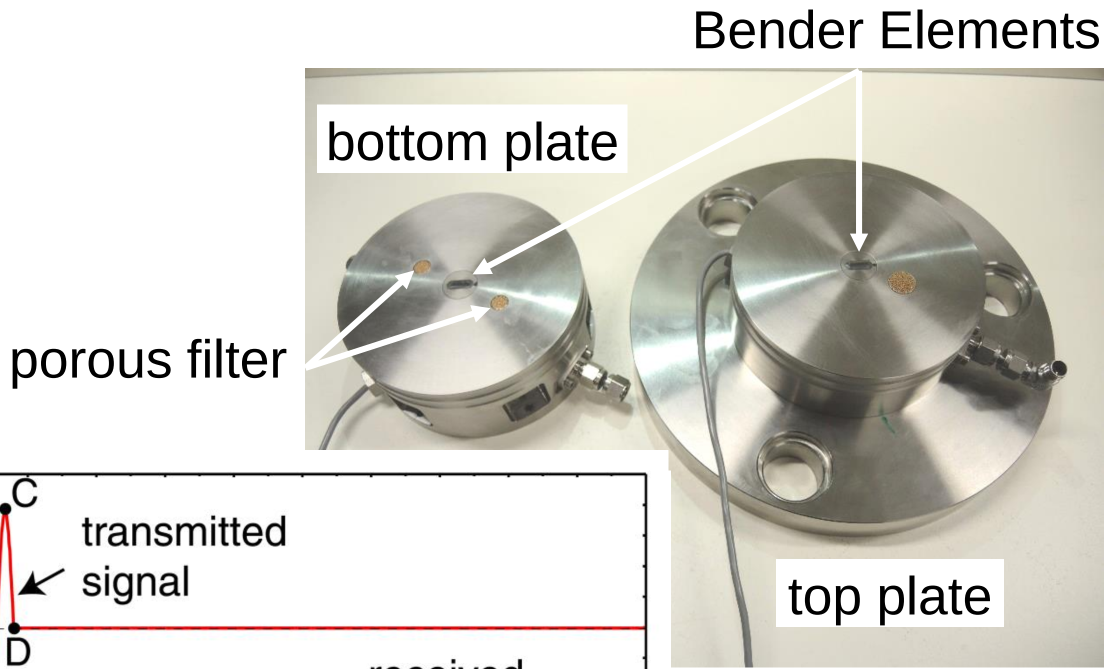
Type 3: Triaxial devices for a large number of fast cycles (f < 2 Hz)

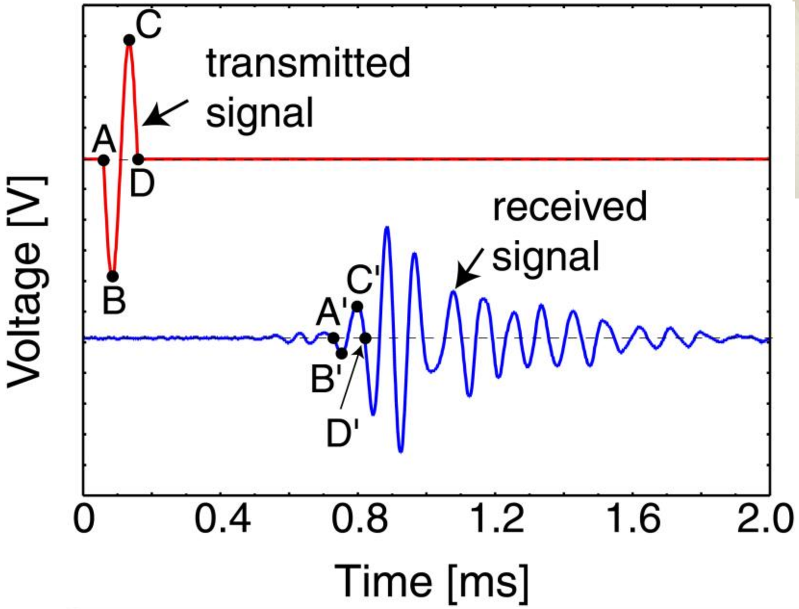
Upgrade of the triaxial device to Bender Elements from 04. – 09.08.2021



Measurement of shear wave velocity by means of Bender Elements





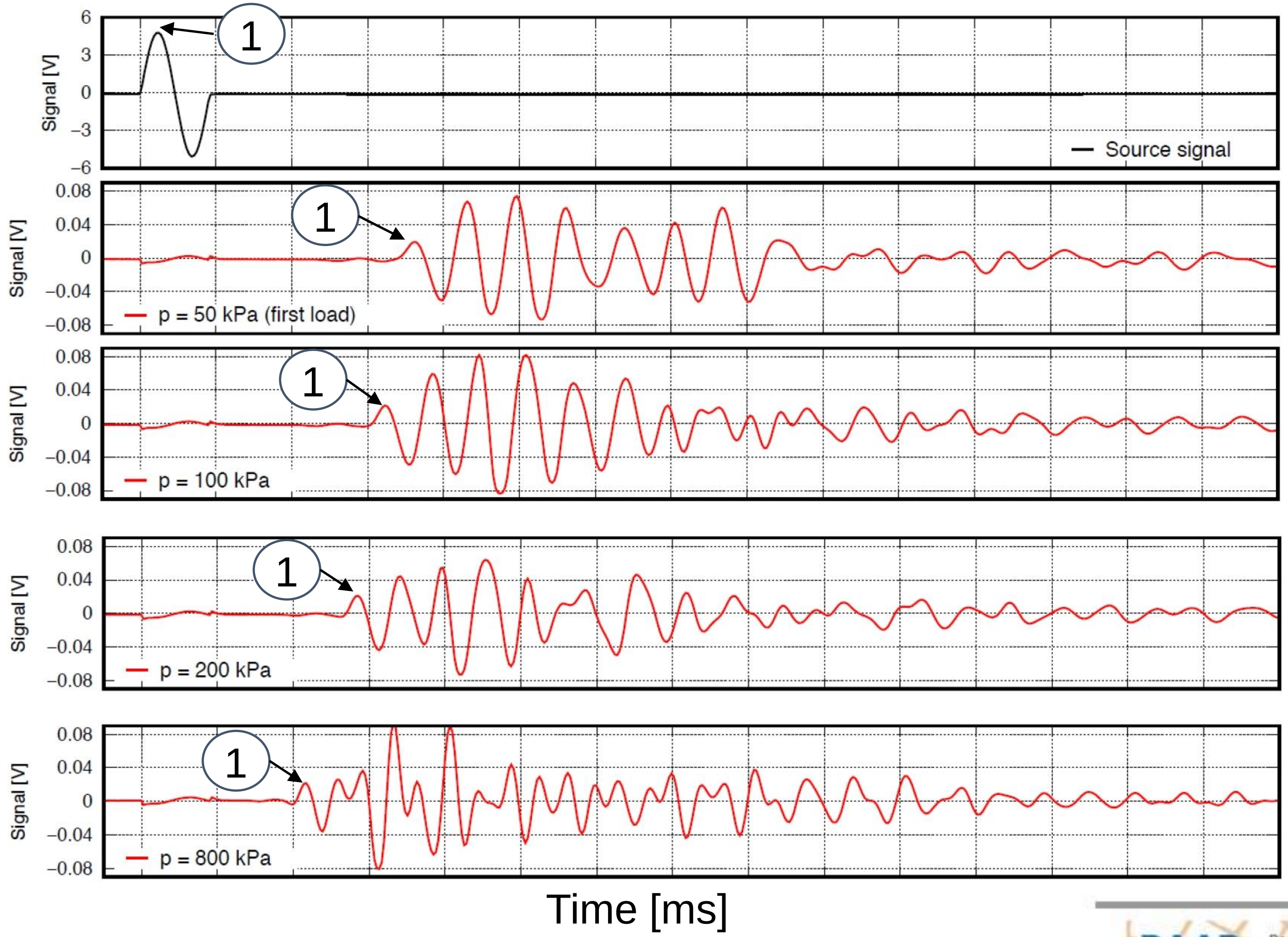


$$v = l/t$$

velocity v
travel length l
time t

Measurement of shear wave velocity by means of Bender Elements

Variation in mean pressure p



Dense sand sample: D_{r0} = 0,86 %

(1) : First peak

S-Wave velocity:

$$v_s = \sqrt{G/\rho} = \sqrt{\frac{E}{\rho} \cdot 2(1+\upsilon)}$$

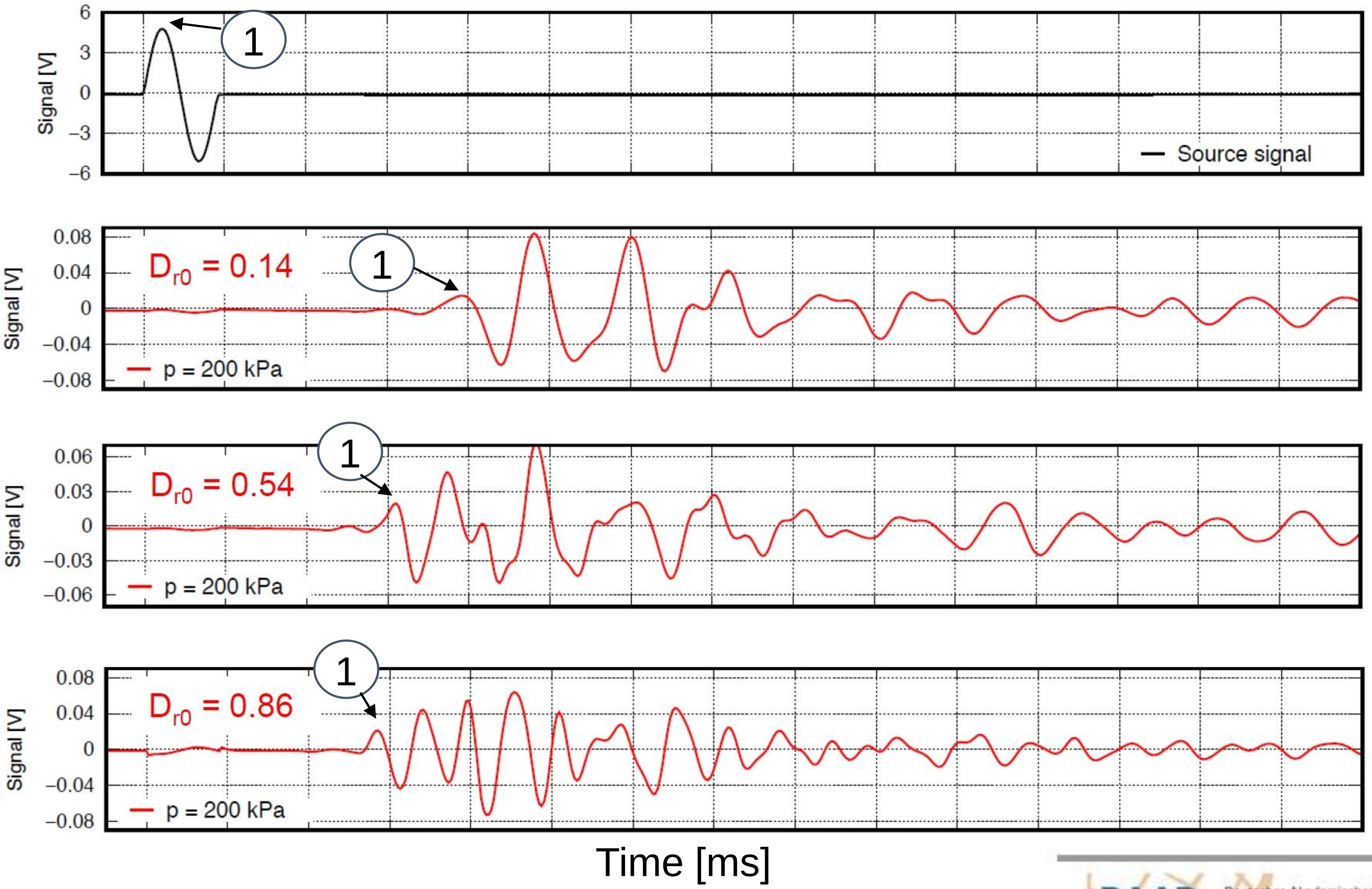
P-Wave velocity.:

$$v_P = \sqrt{\frac{G}{\rho} \cdot \frac{2(1+\upsilon)}{1-2\upsilon}} = \sqrt{\frac{E}{\rho} \cdot \frac{1-\upsilon}{1-\upsilon-2\upsilon^2}}$$

Shear modulus G [kPa]
Density ρ [g/cm³]
Poisson's number υ [-]
Young's modulus E [kPa]

Measurement of shear wave velocity by means of Bender Elements

Variation in relative density D_{r0}



Mean pressure: p = 200 kPa

① : First peak

S-Wave velocity:

$$v_s = \sqrt{G/\rho} = \sqrt{\frac{E}{\rho} \cdot 2(1+\upsilon)}$$

P-Wave velocity.:

$$v_P = \sqrt{\frac{G}{\rho} \cdot \frac{2(1+\upsilon)}{1-2\upsilon}} = \sqrt{\frac{E}{\rho} \cdot \frac{1-\upsilon}{1-\upsilon-2\upsilon^2}}$$

Shear modulus G [kPa]
Density ρ [g/cm³]
Poisson's number υ [-]
Young's modulus E [kPa]

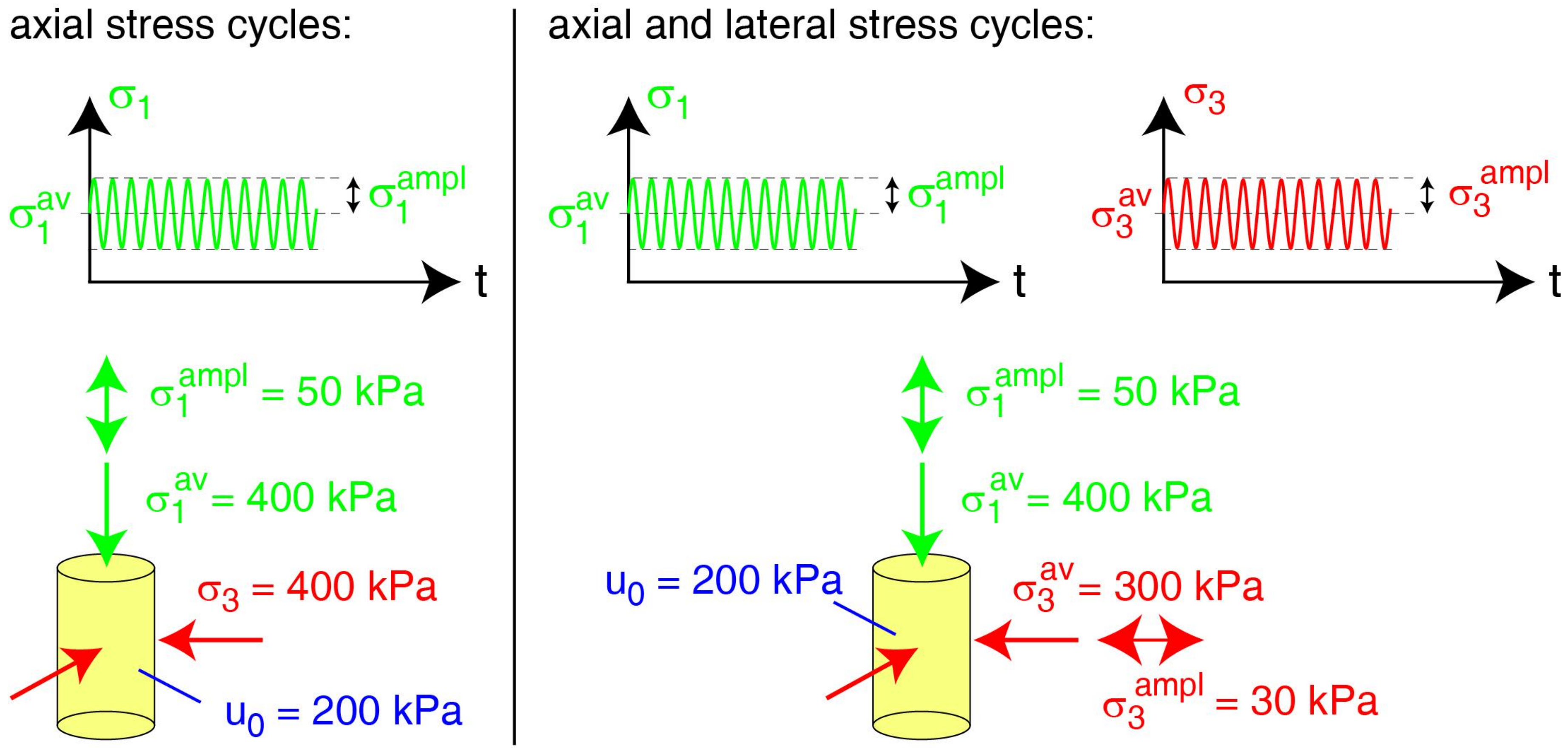
Type 3: Triaxial devices for a large number of fast cycles (f < 2 Hz)

Sample preparation and Bender Elements

Break - Enjoy your meal!

After the break → VIDEO 45 min

Cyclic triaxial tests



Drained cyclic triaxial test

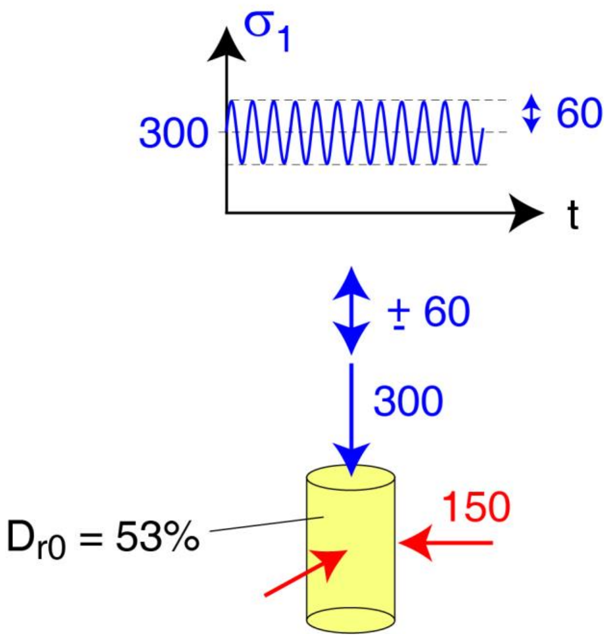
IBF-Test on Karlsruhe fine sand

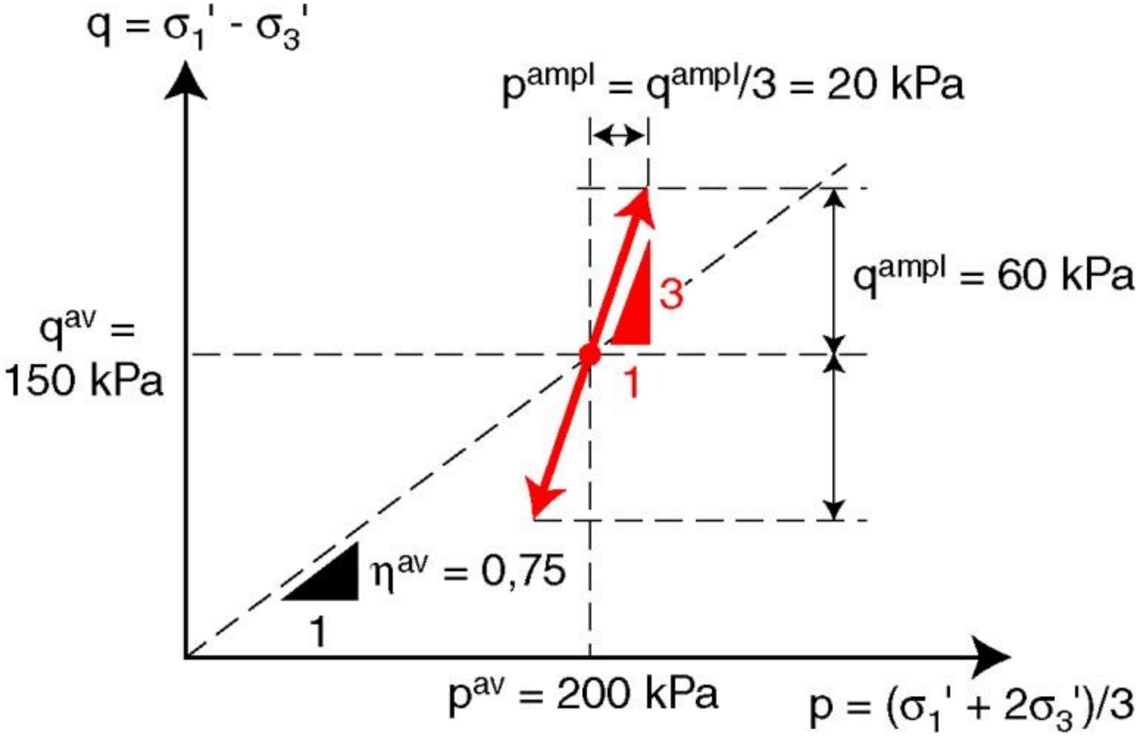
p^{av} = (300 + 2·150)/3 = 200 kPa

q^{av} = 300 – 150 = 150 kPa

$\eta^{av} = q^{av}/p^{av}$ = 150 / 200 = 0,75

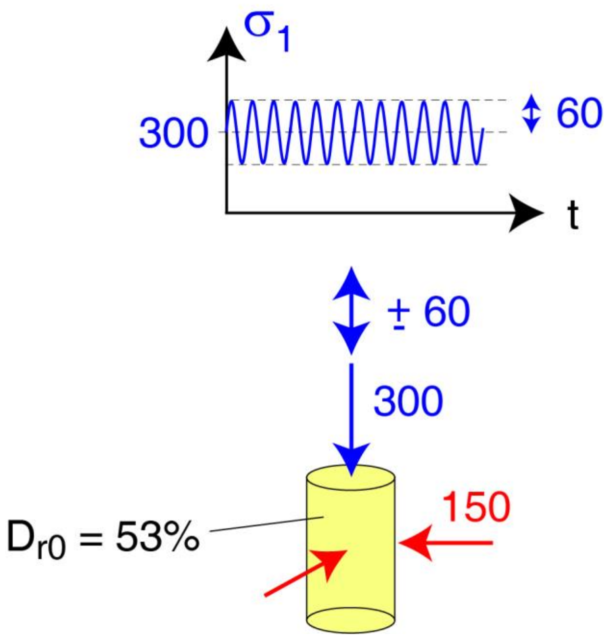
$q^{ampl} = \sigma_1^{ampl}$ = 60 kPa



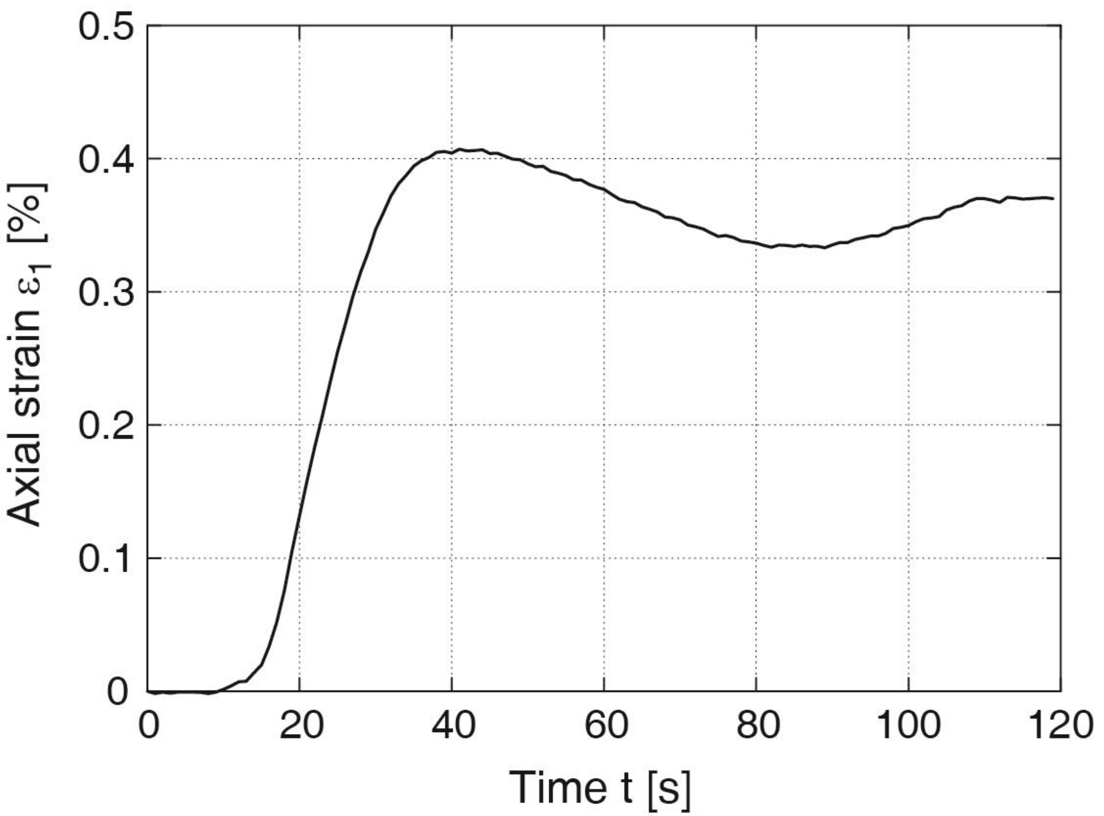


Drained cyclic triaxial test

IBF-Test on Karlsruhe fine sand

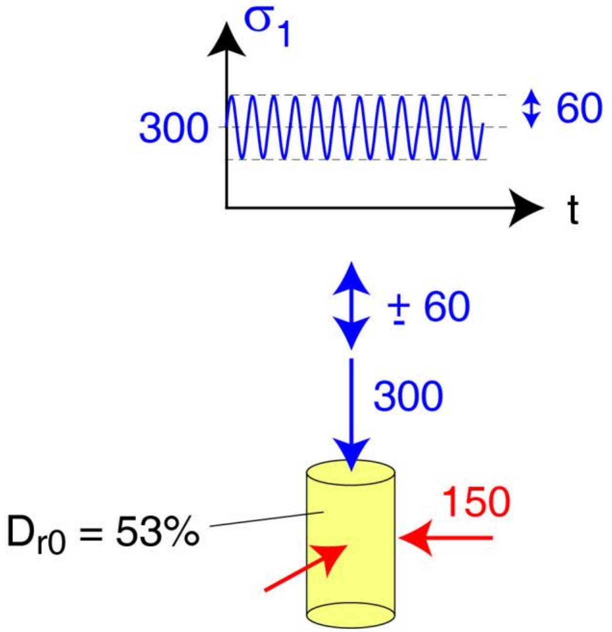


First cycle with loading frequency of 0.01 Hz:

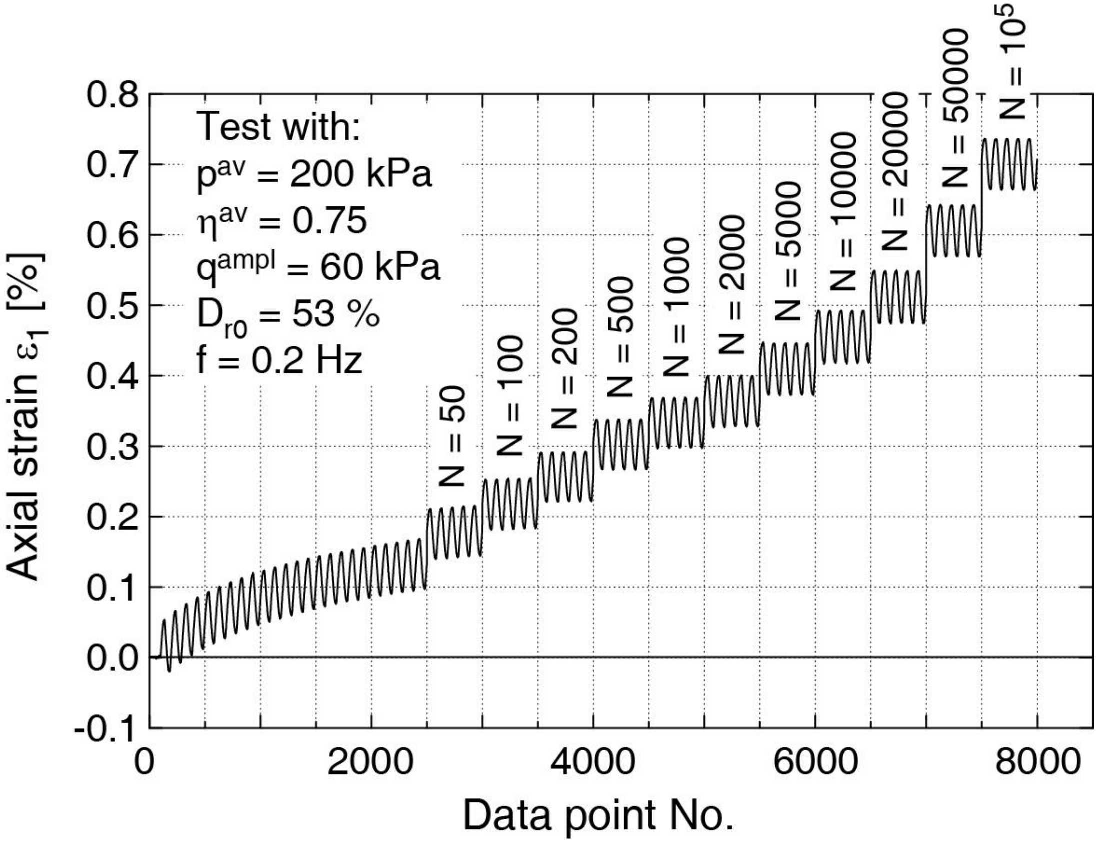


Drained cyclic triaxial test

IBF-Test on Karlsruhe fine sand

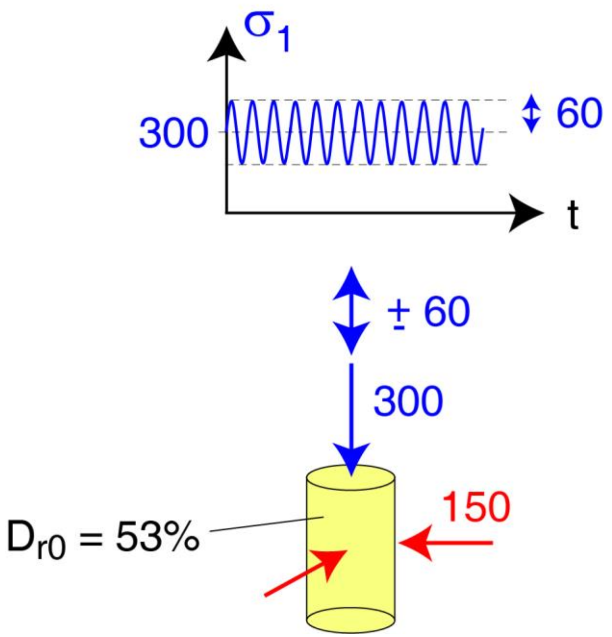


Further 100,000 cycles:

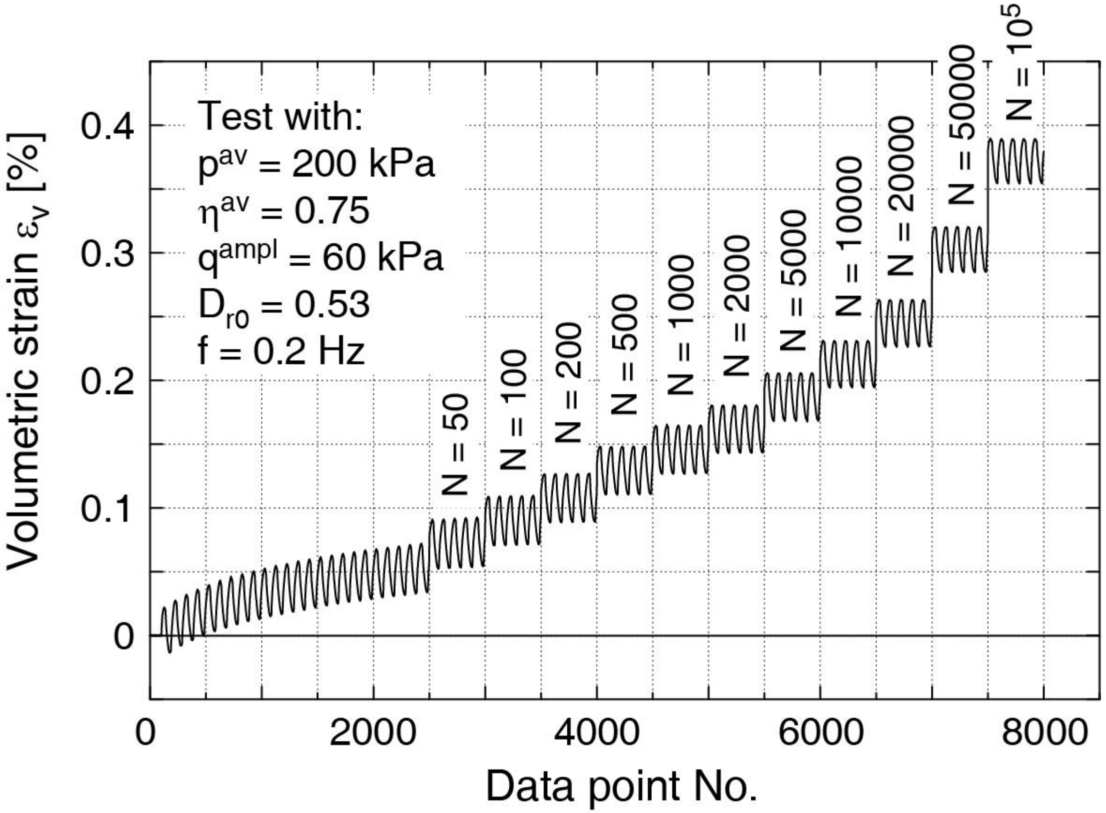


Drained cyclic triaxial test

IBF-Test on Karlsruhe fine sand

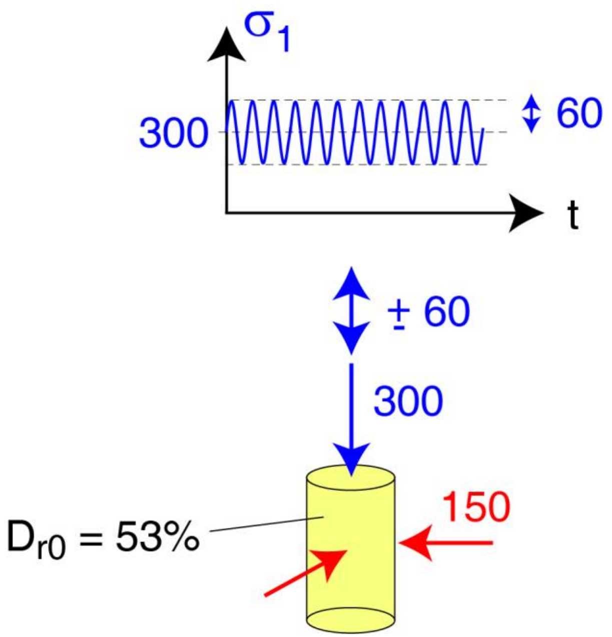


Further 100,000 cycles:

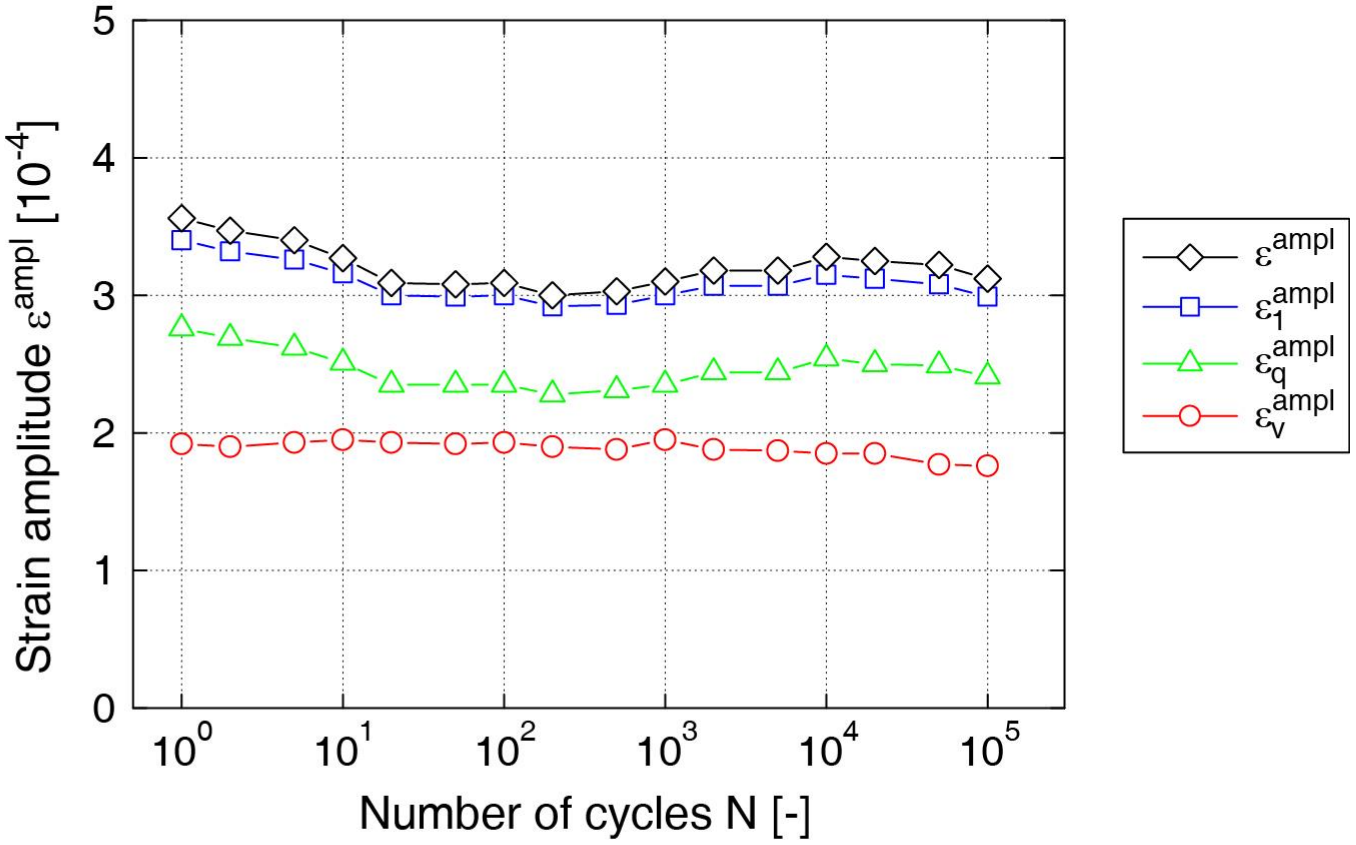


Drained cyclic triaxial test

IBF-Test on Karlsruhe fine sand



Strain amplitudes (elastic deformation component):



Drained cyclic triaxial test

IBF-Test on Karlsruhe fine sand

Lateral strain:

$$\varepsilon_3 = \frac{1}{2}\,(\varepsilon_v - \varepsilon_1)$$

Deviatoric strain:

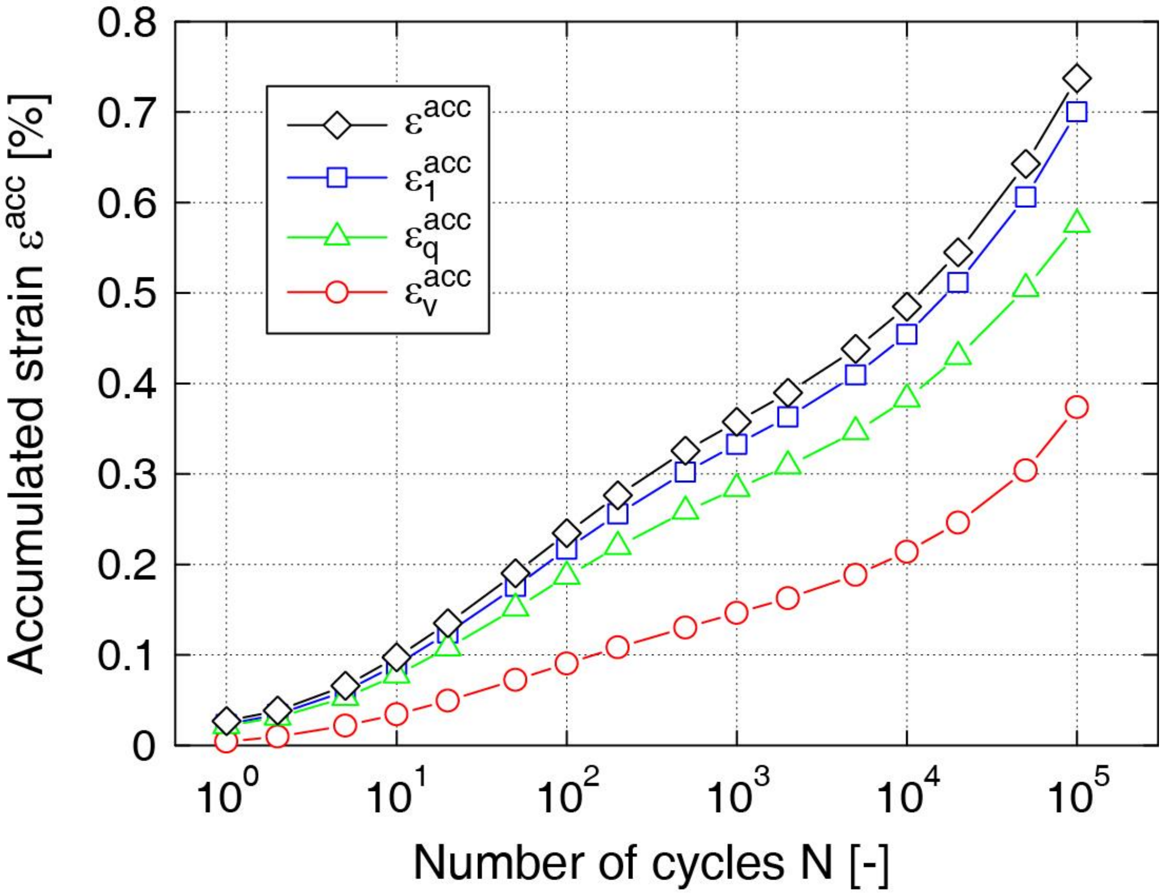
$$\varepsilon_q = \frac{2}{3}\,(\varepsilon_1 - \varepsilon_3)$$

Total strain:

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

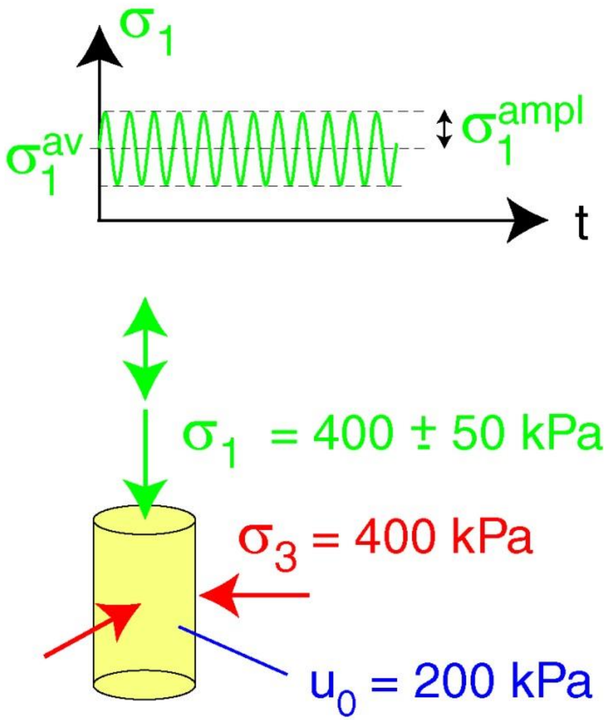
$$\boldsymbol{\varepsilon} = \begin{pmatrix} \varepsilon_1 & 0 & 0 \\ 0 & \varepsilon_3 & 0 \\ 0 & 0 & \varepsilon_3 \end{pmatrix}$$

Accumulated strain (permanent deformation component):

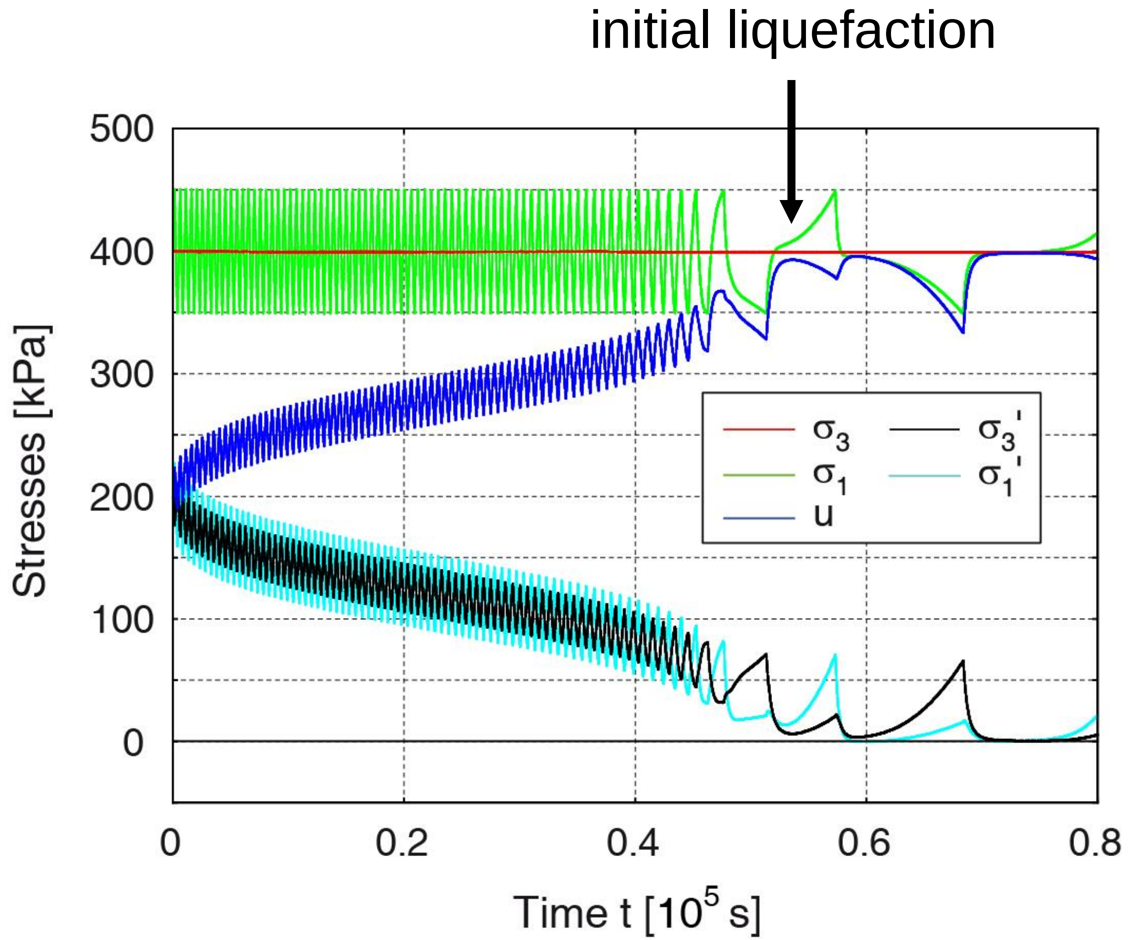


Undrained cyclic triaxial test

IBF-Test on Karlsruhe fine sand

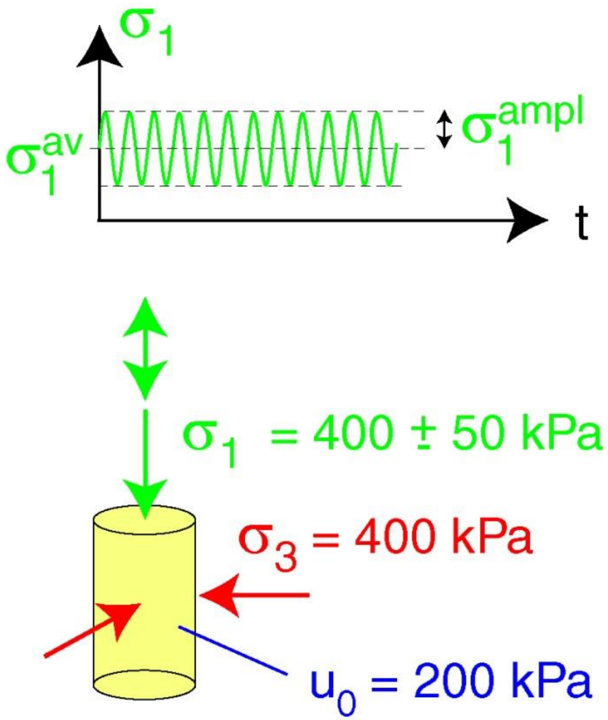


Stresses:



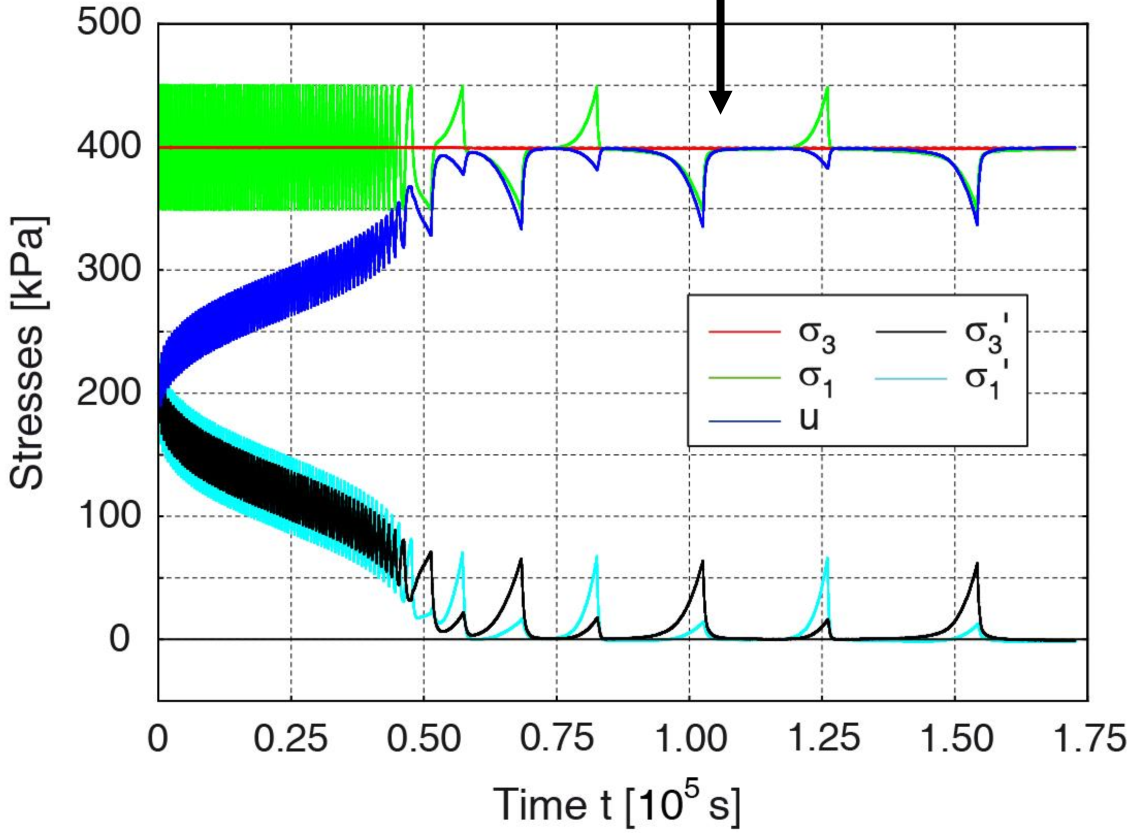
Undrained cyclic triaxial test

IBF-Test on Karlsruhe fine sand



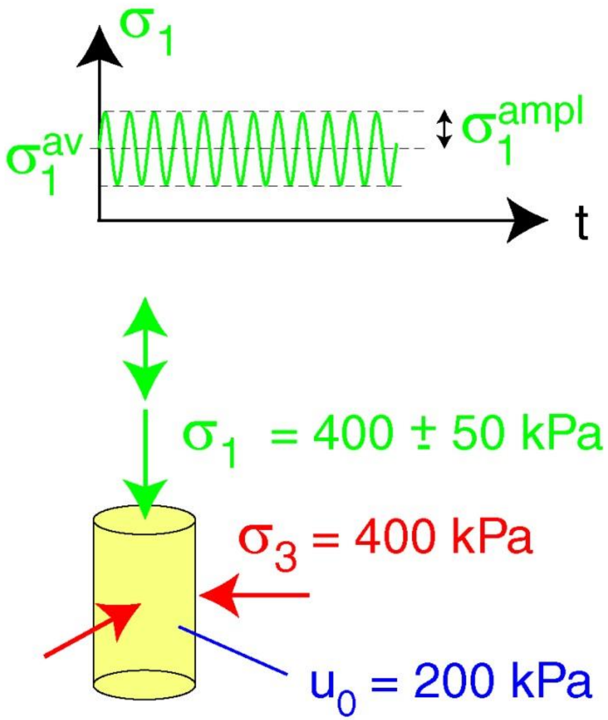
Stresses:

partial liquefaction

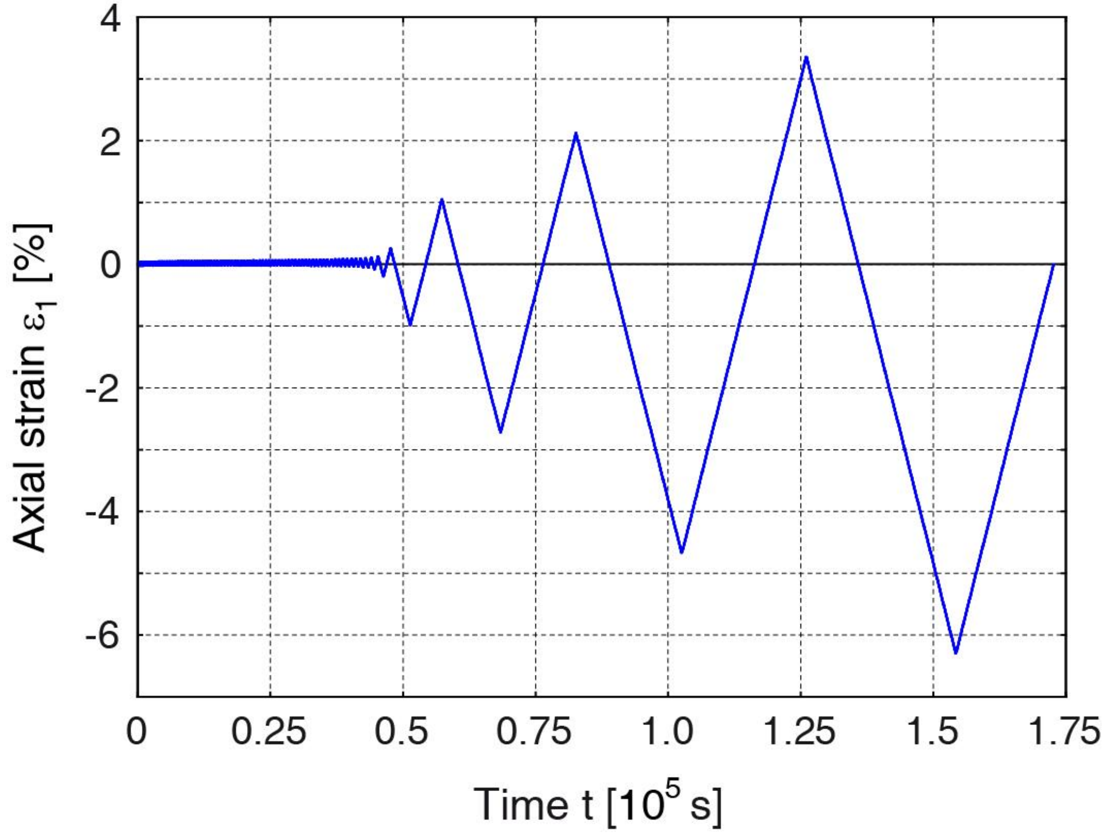


Undrained cyclic triaxial test

IBF-Test on Karlsruhe fine sand

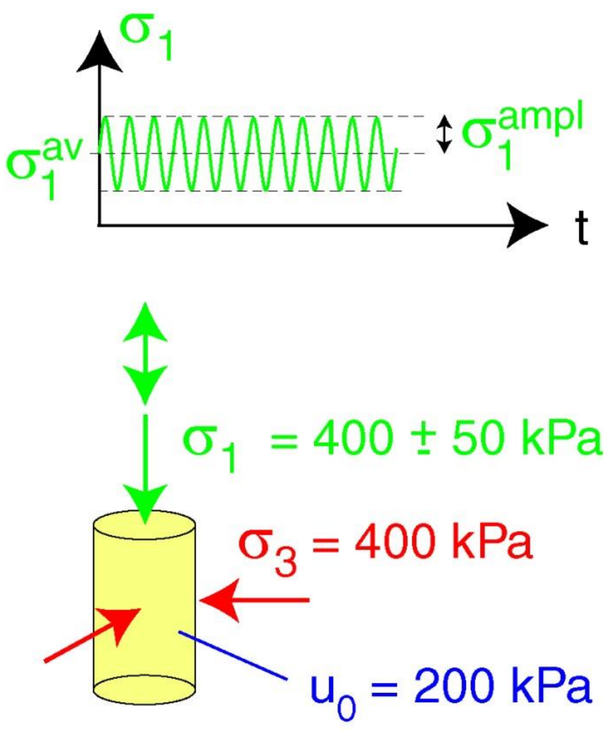


Axial strain:

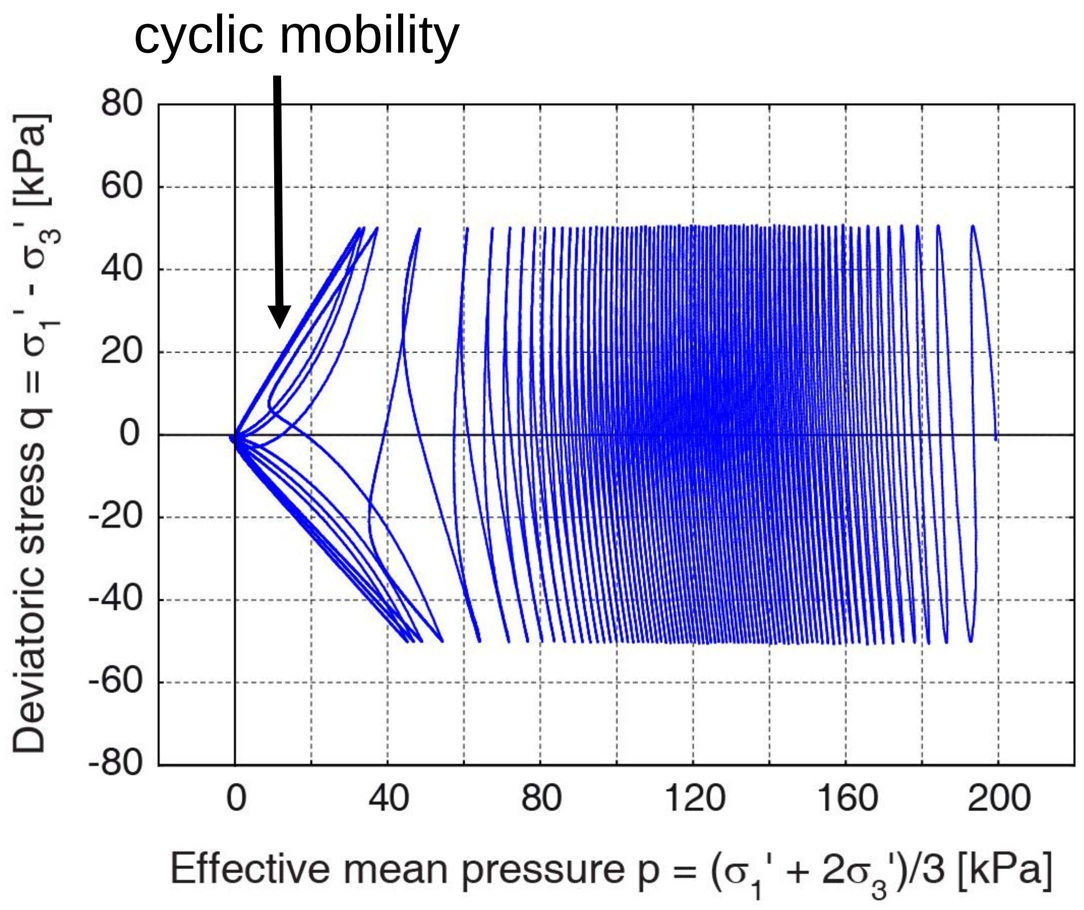


Undrained cyclic triaxial test

IBF-Test on Karlsruhe fine sand

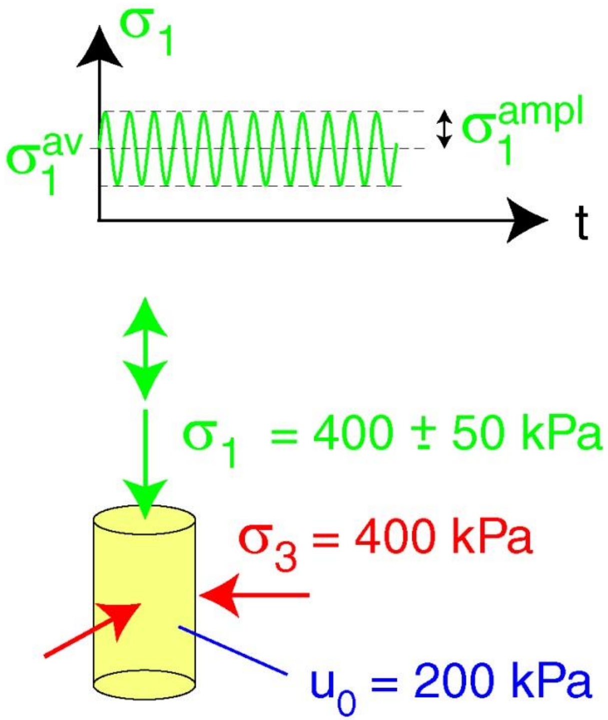


Effective stress path:

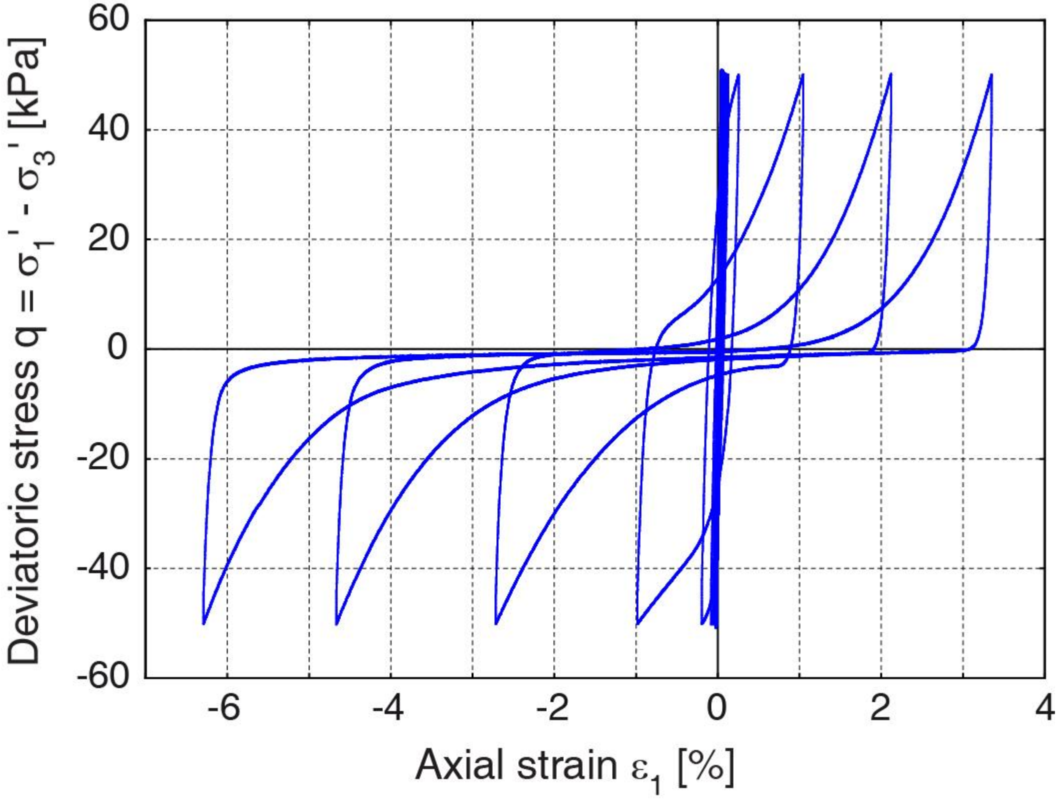


Undrained cyclic triaxial test

IBF-Test on Karlsruhe fine sand



Stress-strain-hysteresis:



Type 4: Hollow cylinder device for complex loading

measurement and control equipment

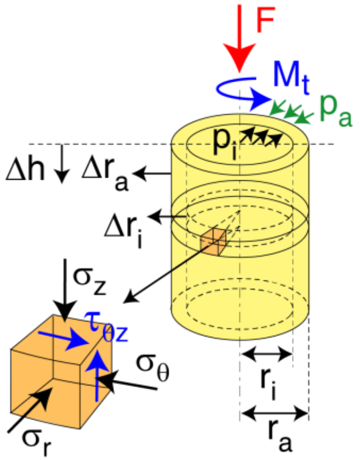
dashboard with burette system

plexiglas cylinder

outer cell pressure controller

back pressure Controller

inner cell pressure controller

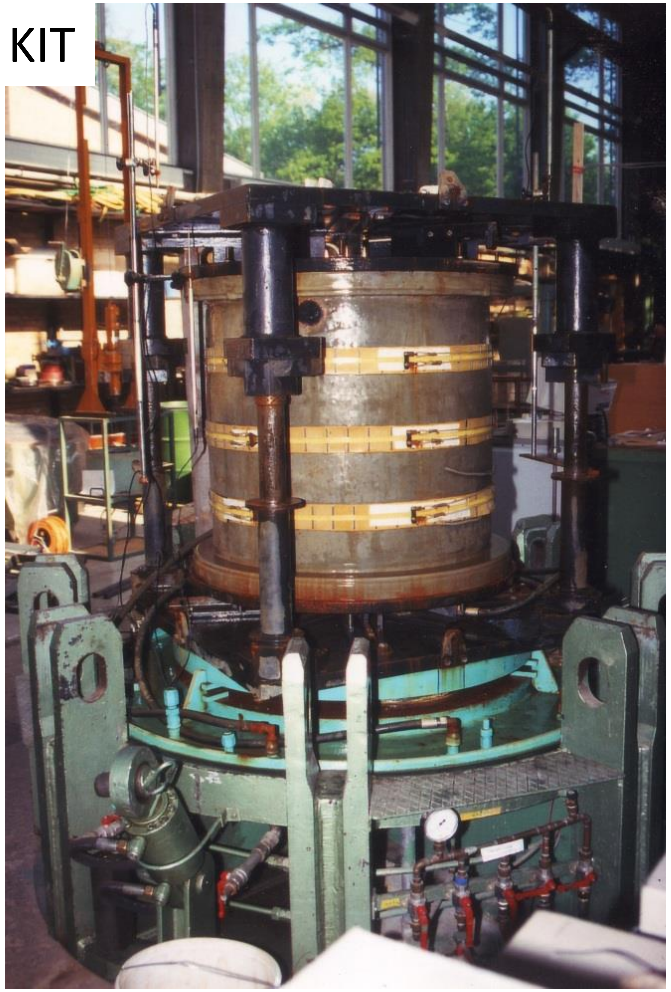


Independent variation of:

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

Type 5: Large triaxial device for large specimens

KIT

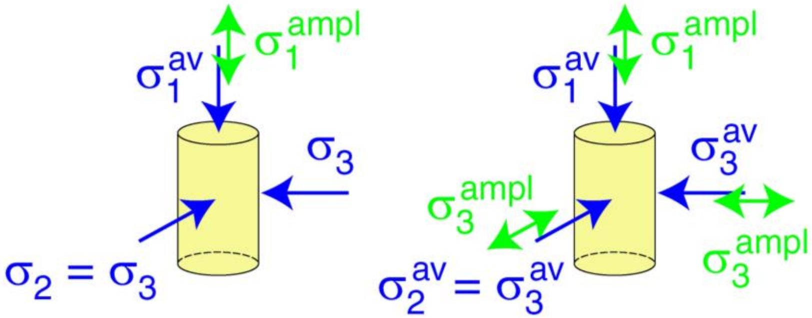


KIT

Maximum possible specimen dimensions:
Diameter d = 1m,
Height h = 1.8 m

Patras

Thank you for your attention



Patras

Various pictures where taken from *Lecture notes on Geotechnical Engineering* by Prof. Torsten Wichtmann (Bauhaus-University Weimar, 2018). Thank you for your kind permission to use them!