Challenges associated with laboratory testing on Opalinus Clay, test interpretation and definition of rock mechanical properties

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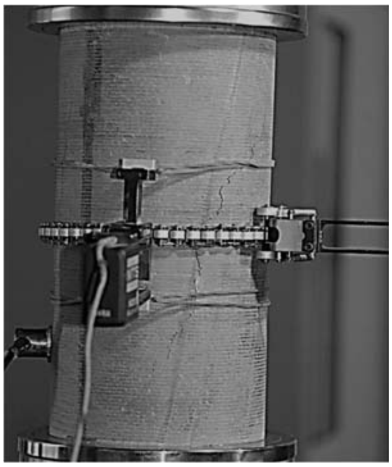


Symposium Felsmechanik und Bautechnik, Zürich, 14.02.2014

Challenges

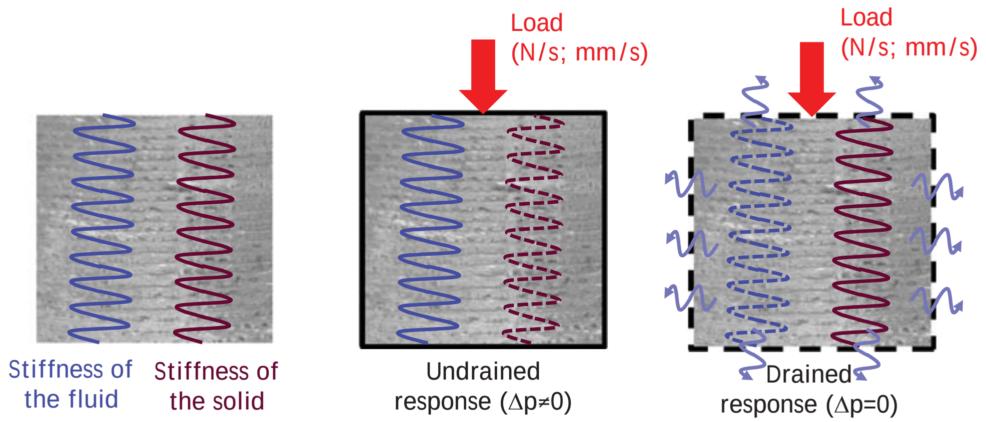
Clay Rock Behaviour

- Initially saturated material with very low hydraulic conductivity
- Strong hydro-mechanical coupled behaviour
- Strength and stiffness anisotropy
- Sensitiveness to moisture changes
- Non-linear failure behaviour
- Time dependent deformations (consolidation, creep, viscoelasticity, clay mineral swelling)

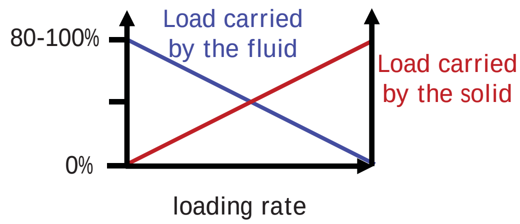
Technical Issues

- Calibration
- Pore pressure control +
- Sufficient machine stiffness and load capacity (axial and radial pressure) +
- Extremely low loading rates
- Often long test durations
- Robustness of the equipment, temperature issues…
- Monitoring set-up → measured response versus actual specimen response

Saturated poro-elastic medium



Undrained test: combined response of the fluid and the solid phase
→ the two responses can be decomposed by measuring the fluid pressure during loading and the effective stress in the solid can be calculated



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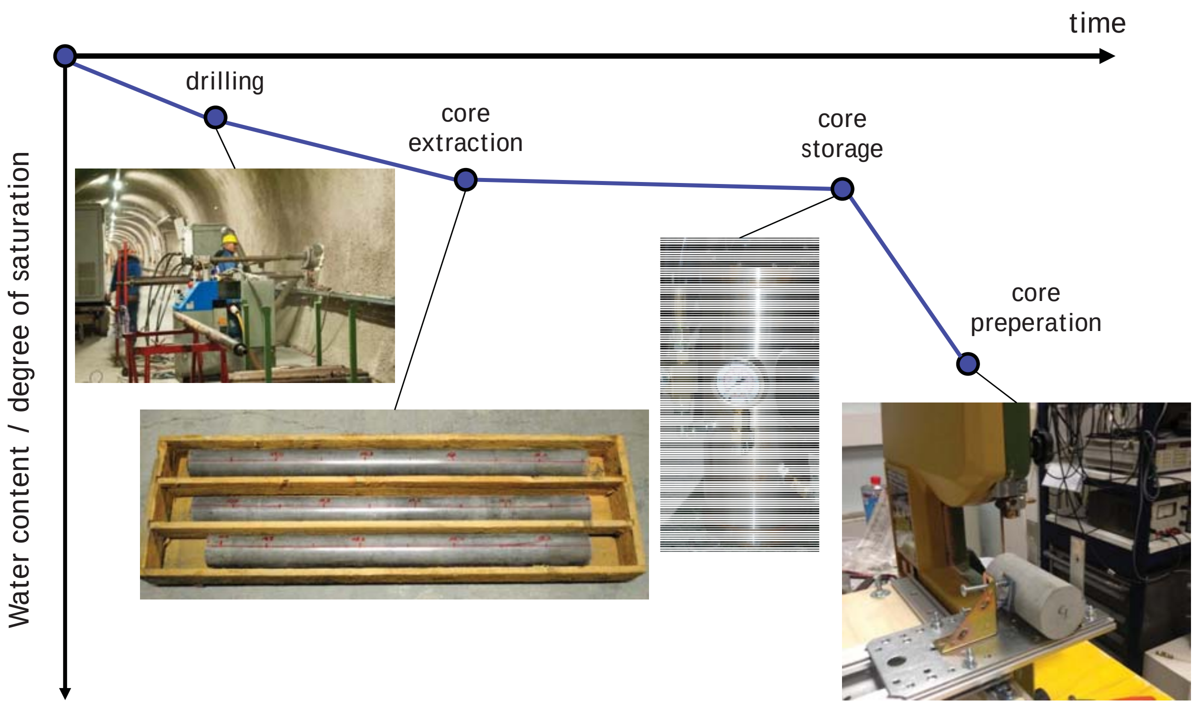
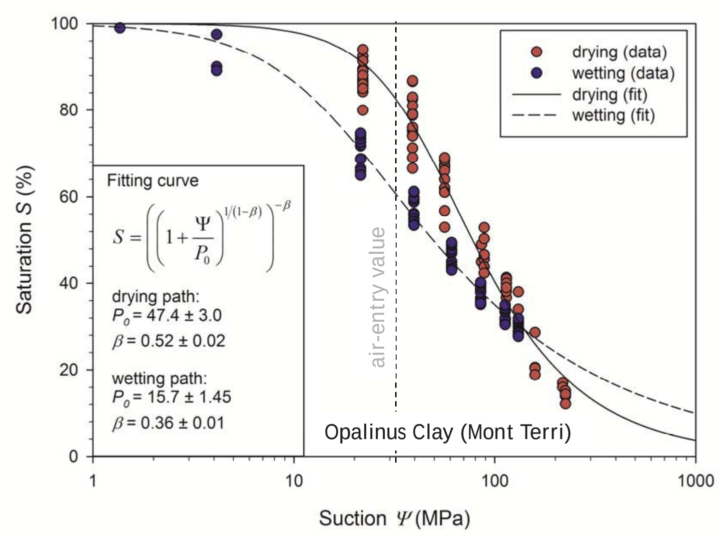
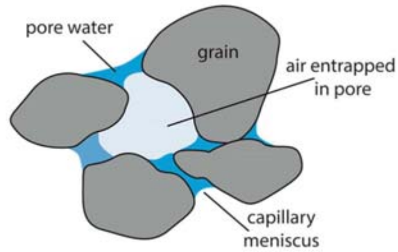
Saturated ?

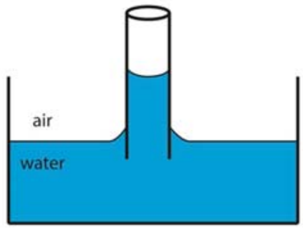


Capillary Forces

Water Retention Characteristics

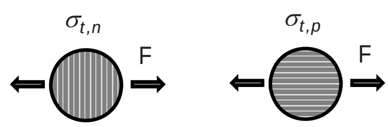




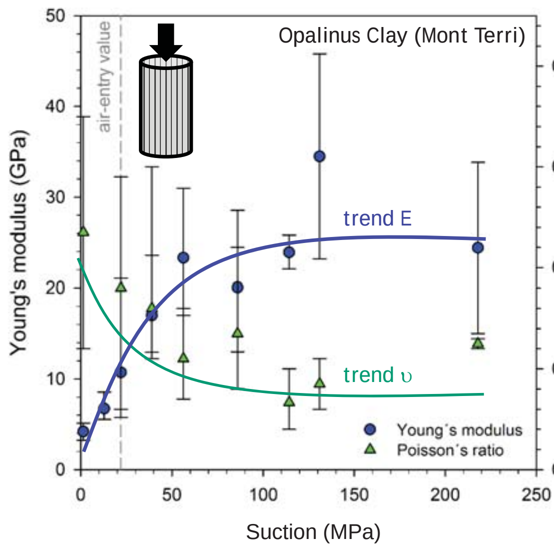


Wild et al. (in review)

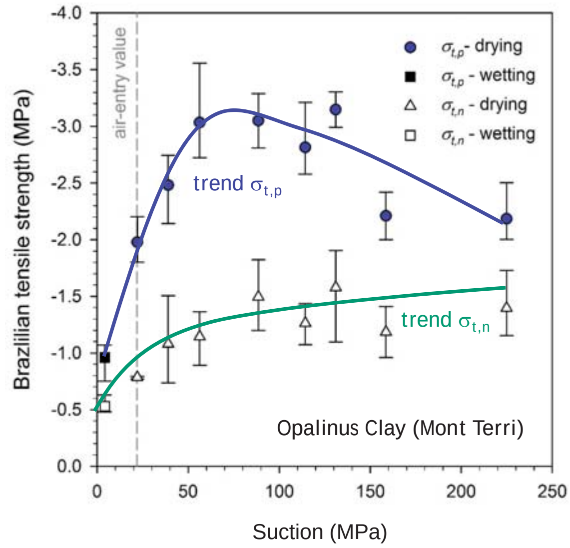
Capillary Forces



Elastic Properties



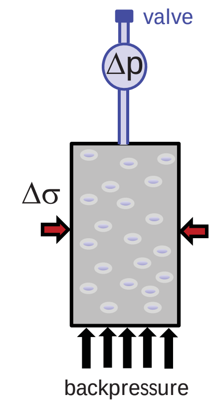
Tensile Strength

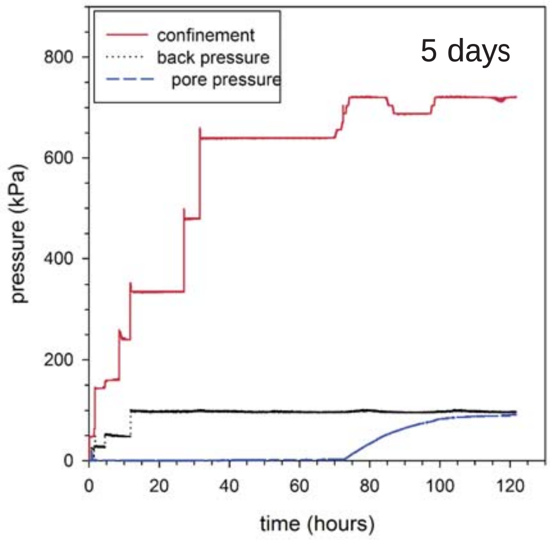


Wild et al. (in review)

Challenge of saturation

Flushing Phase





The flushing phase is known to be somewhat ineffective →
After the flushing phase compressible air bubbles may still be present
→ Have to be dissolved in the subsequent saturation procedure
→ Back-Pressure Cycles

De-aired brine („Pearson-Water“)

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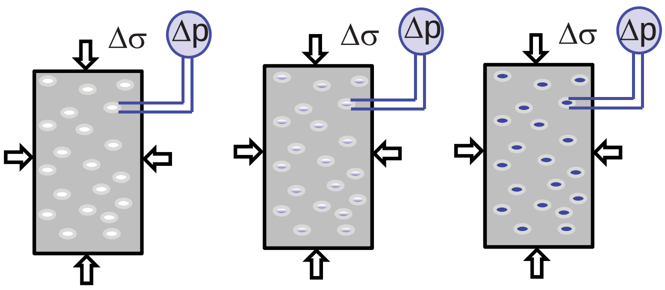
Challenge of saturation

Soils:	
air:	compressible
water:	incompressible
solid:	**incompressible**

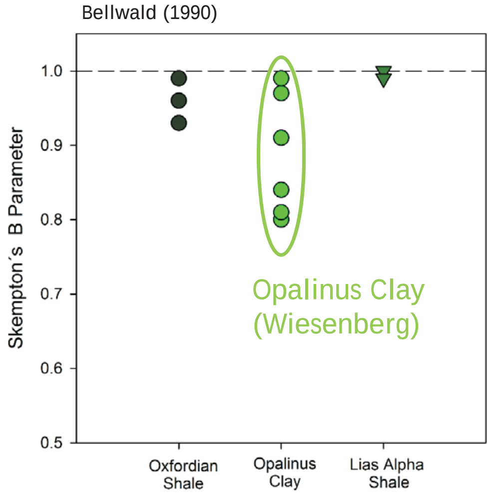
Clay shales:	
air:	compressible
water:	incompressible
solid:	**compressible**

undrained isotropic loading $B=\Delta p/\Delta\sigma$

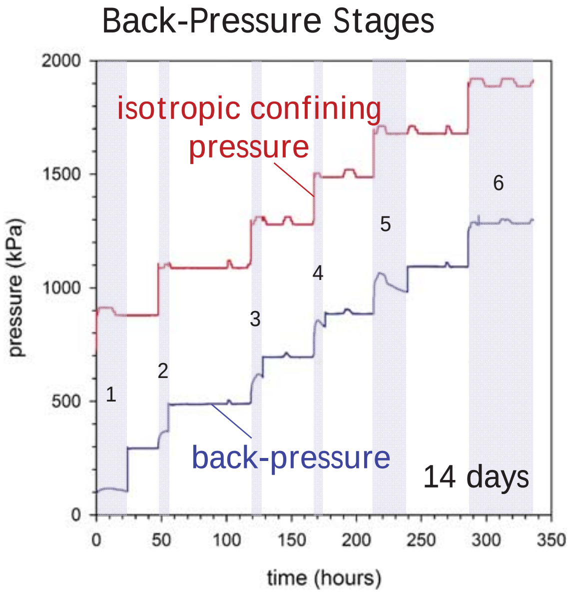


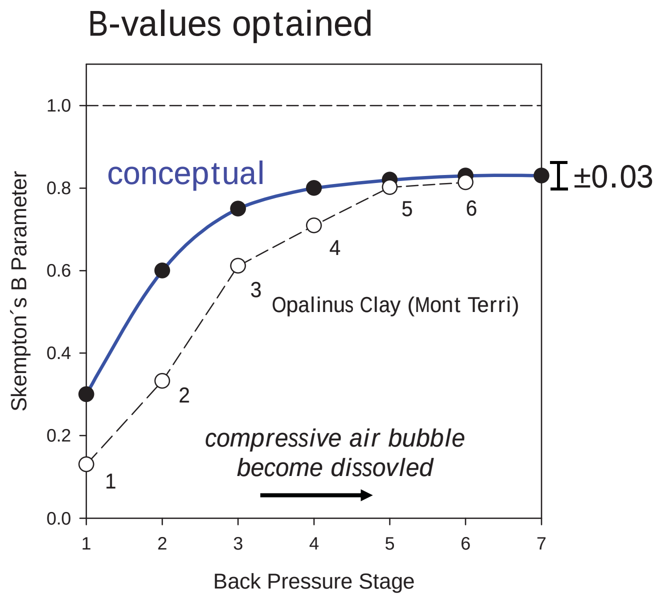
B=0 B<1 B=1 saturated!

Aristorenas (1992)
Bellwald (1990)



Challenge of saturation





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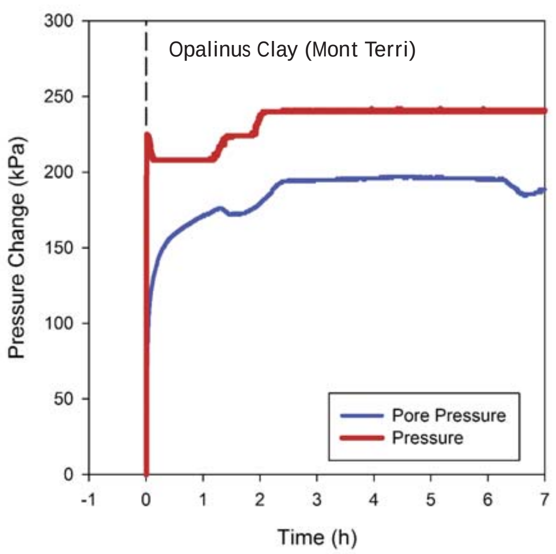
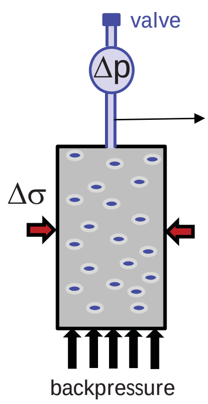
Challenge of pore pressure measurement





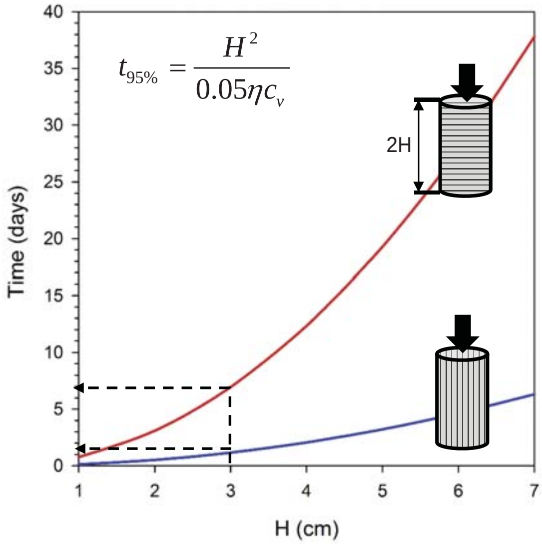
specimen´s pore fluid is connected to the valve

system is compliant and adds apparent porosity

→ Upon loading the pore pressure in the sample may change instantaneously, but the pore pressure measured may depend on the loading rate

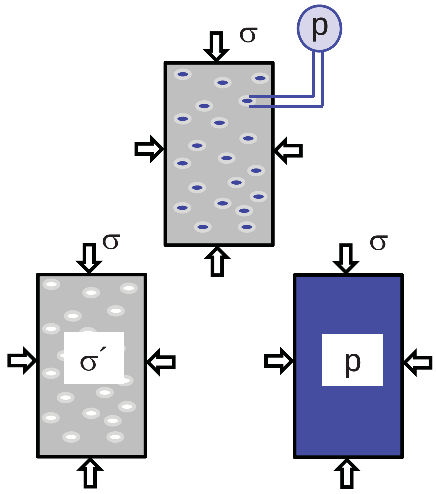
Undrained versus drained loading

Drained compression (Δp=0)



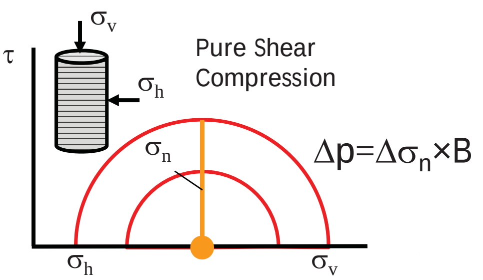
Bishop and Henkel 1957

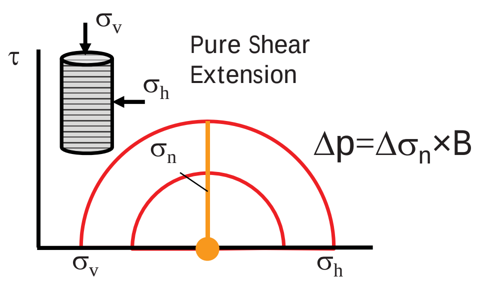
Undrained compression (Δp≠0)

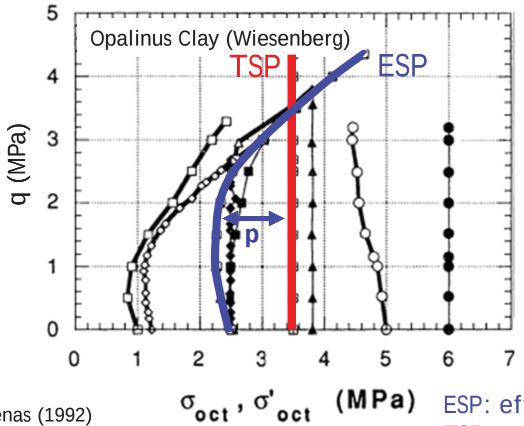


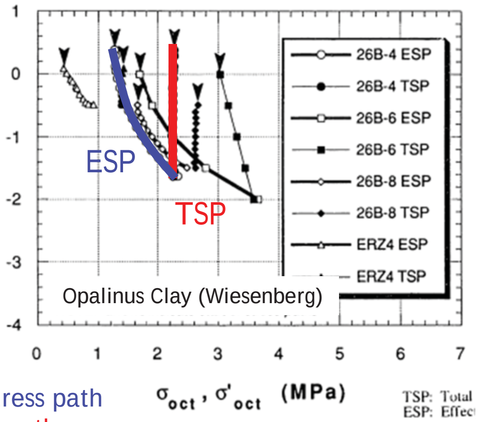
Decompose: σ´ = σ - p

Aspects of undrained behaviour







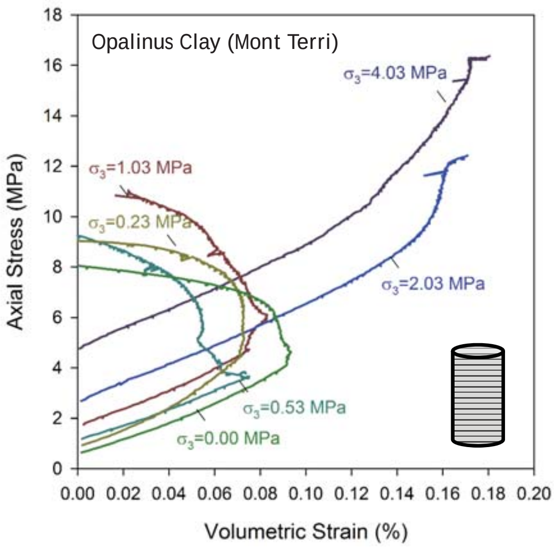


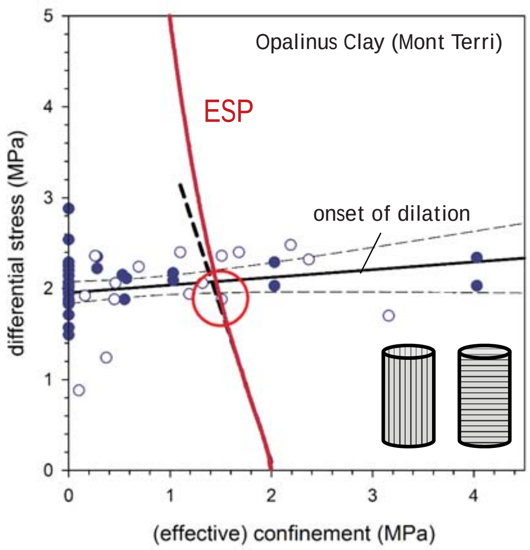
Aristorenas (1992)
Bellwald (1990)

ESP: effective stress path
TSP: total stress path

TSP: Total
ESP: Effec

Aspects of undrained behaviour





Amann et al. 2010, 2011

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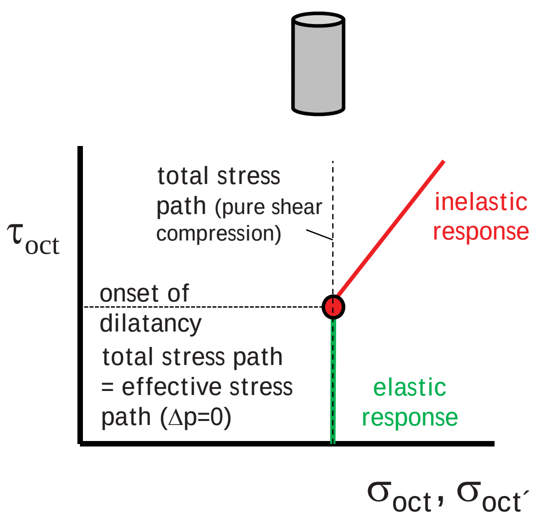
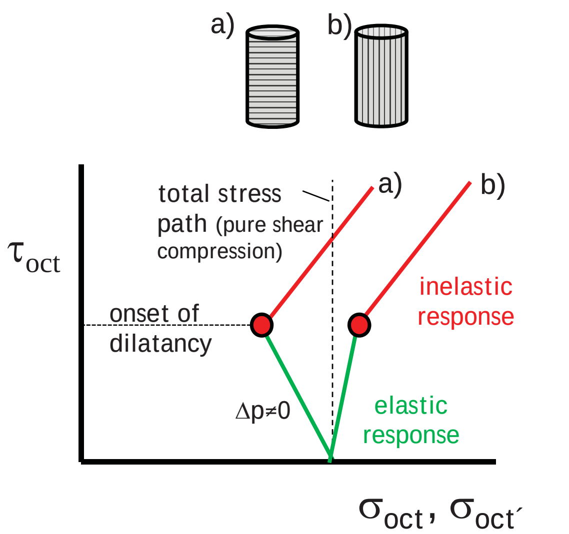
Pore Pressure evolution - conceptual

linear-elastic, brittle material

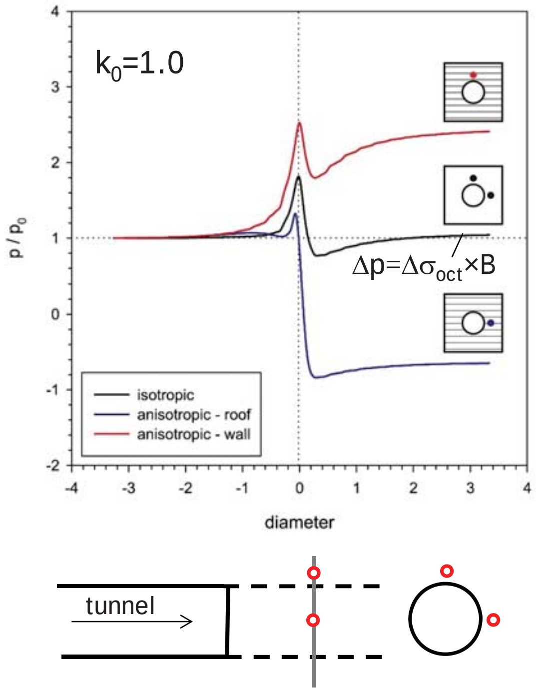
$\Delta p = \Delta\sigma_{oct,n} \times B \rightarrow (\varepsilon_v = 0)$



transversal-isotropic, brittle material

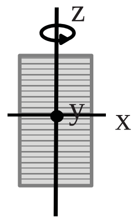


Elastic behaviour and simplifications



For describing a transversal isotropic poro-elastic material, 7 independent variables are required:

$E_{x,u}$, $E_{z,u}$, $\nu_{yx,u}$, $\nu_{zx,u}$, G_{zx}, B_x, B_z



The cross shear modulus G_{zx} cannot be determined from triaxial tests on cylindrical specimens

The two Skempton´s Parameter are additionally needed to calculate effective (drained) elastic properties

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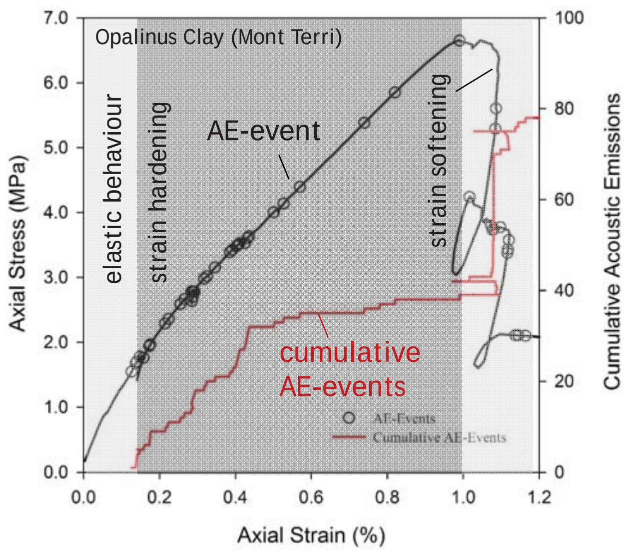
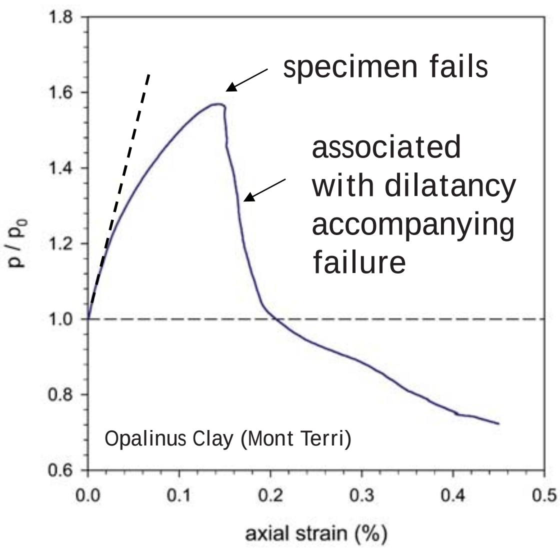
Aspects of undrained behaviour

non-linear stress-strain response

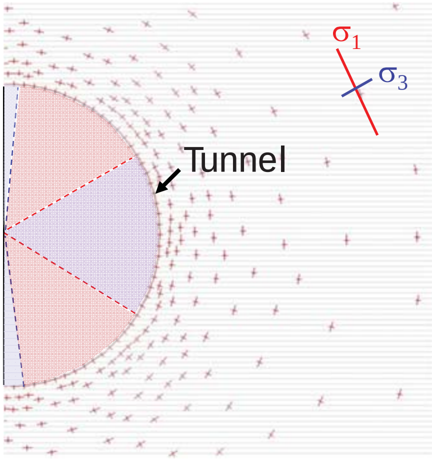


pre- and post-failure Δp

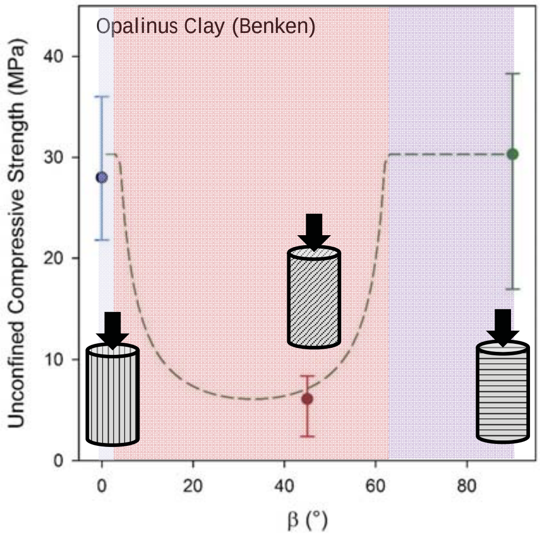


Anisotropic Strength

Stress trajectories

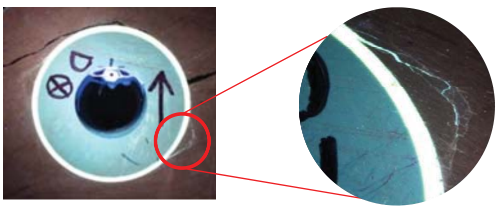


Anisotropy in strength

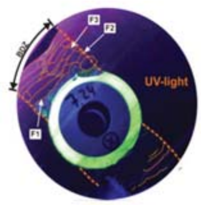


NAB 08-48, NIB 99-39, NIB 99-36b

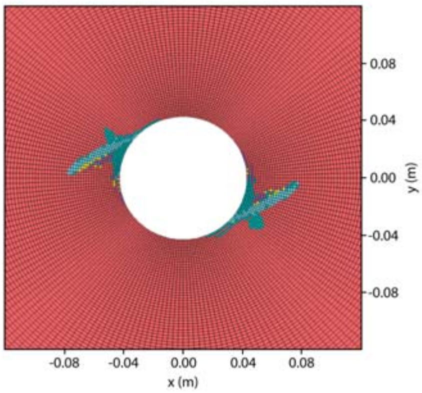
Calibration of numerical models



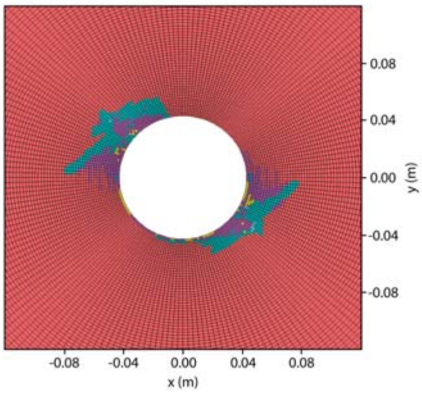
19 h after drilling
(Kupferschmied 2013)



2 y after drilling
(Jaeggi et al. 2010)



undrained response



30 days of pore pressure dissipation

Summary

- Challenges are not only associated with the material behaviour → requirements on the testing device combining pore pressure measurement, testing stress states close to the in-situ state, and high control on loading rates
- Mathematical models demand for effective rock properties which can be obtained by 1) drained testing (Δp=0; *assure saturation, extremely slow loading rates, superimposed behaviors, temperature effects*) or 2) undrained testing (Δp≠0) with reliable measurements of the pore pressure response (*assure saturation, system response, effective properties are calculated*)
- Challange to fully quantify effective parameters of a transversal isotropic elastic, brittle/non-linear failing anisotropic solid

Zusammenfassung

- Herausforderungen nicht nur bezüglich des Materialverhaltens → Anforderungen an das Testgerät, d.h. Porendruck-Messung, Test unter in-situ Spannungsbedingungen und sehr gute Kontrolle der Belastungsraten
- Mathematische Modelle verlangen nach effektiven Felseigenschaften durch 1) drainierte Tests (Δp=0; *Probensättigung, sehr geringe Belastungsraten, überlagernde Prozesse, Temperatureffekte*) oder 2) undrainierte Tests (Δp≠0) mit belastbarer Messung des Pordendrucks (*Probensättigung, Systemverhalten, effektive Eigenschaften werden rechnerisch ermittelt*)
- Herausforderung die effektiven Parameter eines transversal isotropen elastischen, spröd/nicht-linear versagenden, anisotropen Materials zu quantifizieren

Thank you for the attention

ENSI (Dr. Erik Frank)
Linda Wymann
Sebastian Zimmer
Reto Thöny
Prof. Dr. Derek Martin

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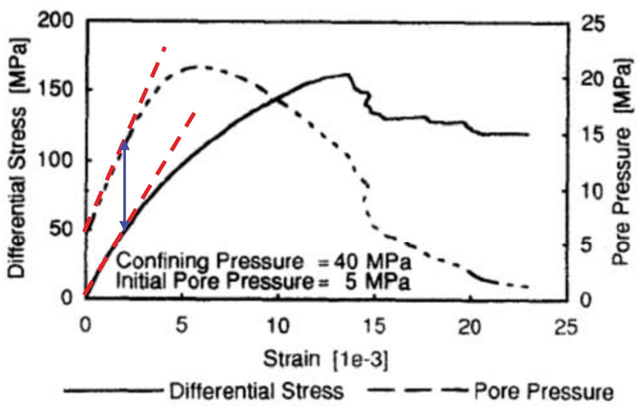
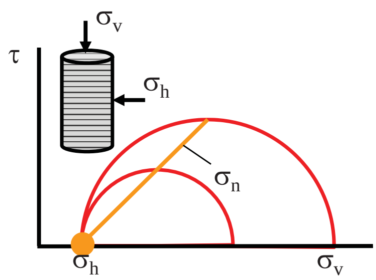
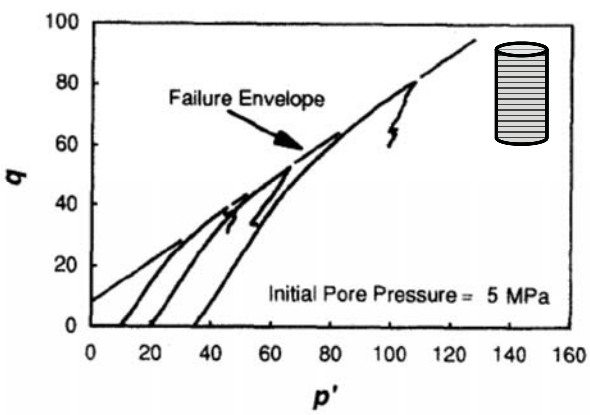
Undrained loading



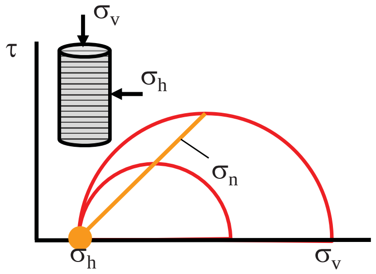




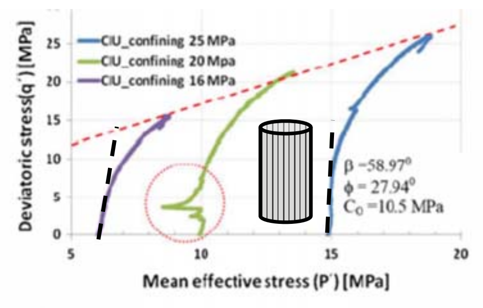
Failure envelope can be described as linear although the stress path deviates from linearity when approaching failure

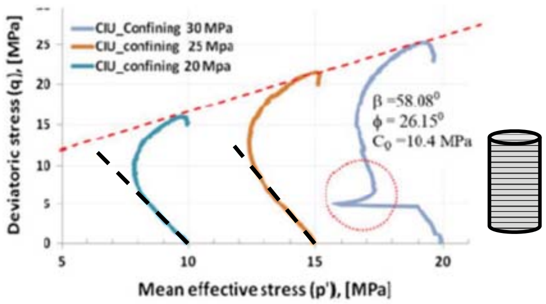
Akoi et al. 1993

Undrained loading



Failure envelope can be described as linear although the stress path deviates from linearity when approaching failure





Islam & Skalle (2013)

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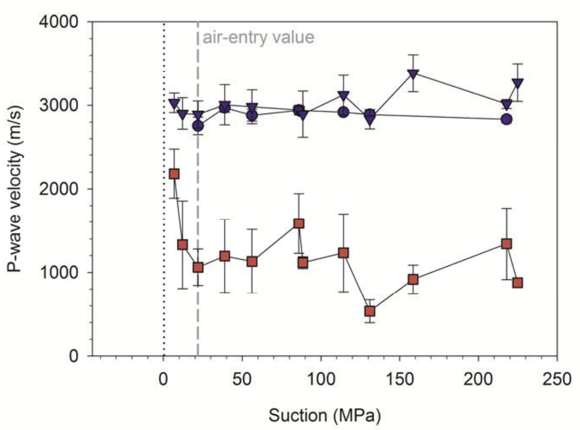
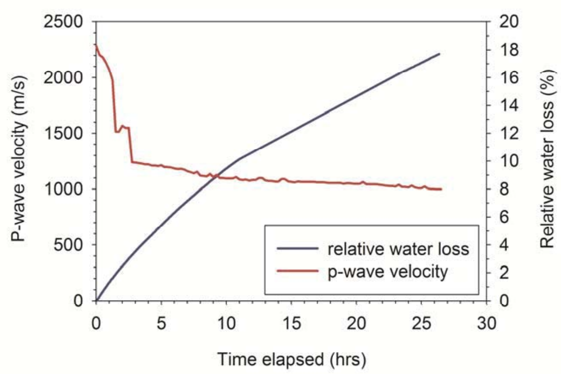
Capillary Forces





Wild et al. (2014)