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February 14th , 2014, Zürich

ETH zürich

Symposium «Rock Mechanics and Rock Engineering of Geological Repositories in Opalinus Clay and Similar Claystones»

Lab Experiments for Determining the Mechanical Behavior of Shales and Claystones

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Outlines

- Introduction and Objectives
- Petrophysics of Shales and Claystones
- Tests for Mechanical Behavior Characterization
- Micro-Structural Analysis of Cracking in Shale
- Concluding Remarks

Acknowledgement

- Institut de Radioprotection et de Sûreté Nucléaire (IRSN)
- Agence Nationale pour le Stockage et la Gestion des Déchets Radioactifs (ANDRA)
- French Railways Company (SNCF)

- **PhD Students:**

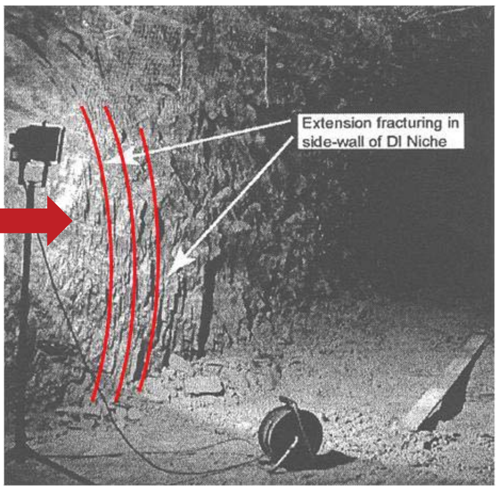
  Eric Boidy, Géraldine Fabre, Attila Hajdu, Mohamad Keshavarz

Introduction and Objectives

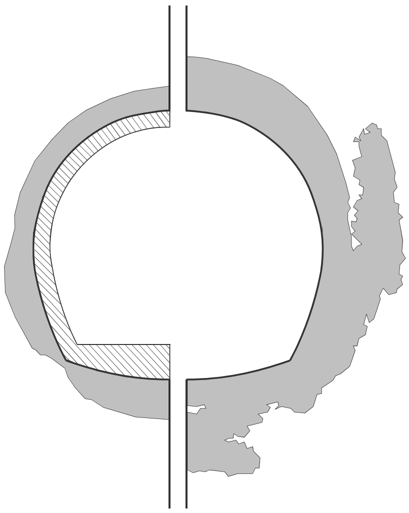
Why: **Prediction of the mechanical behaviour of underground radioactive waste repositories**

What: **Assessment of the extension of the Excavation Damage Zone (EDZ) accounting for time dependency**

EDZ



Mont-Terry Lab



Extension of the EDZ 300 years after the excavation (from numerical modelling

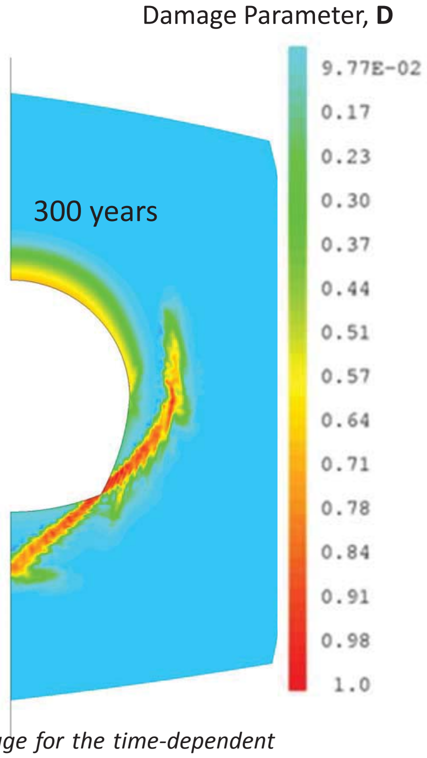
Introduction and Objectives

How: **Constitutive model accounting for time-dependent damage (rate dependent model**

$$\dot{\boldsymbol{\varepsilon}}^{vp} = \frac{\partial\Omega}{\partial\sigma_{ij}} = \frac{3}{2}\,\frac{1}{1-D}\left[\frac{\sigma_{eq}}{(1-D)\;K\;p^{1/M}}\right]^{N}\frac{\mathbf{S}}{\sigma_{eq}}$$

where Ω is the viscoplastic potential, K, N and M are **the viscoplastic parameters** of the rock, σ_{eq} is the von Mises stress and **S** is the stress deviator.

Parameters identification and calibration ???

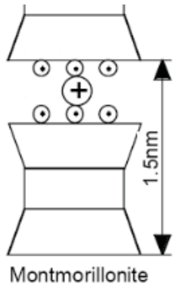


Pellet, F.L. et al. A viscoplastic constitutive model including anisotropic damage for the time-dependent mechanical behaviour of rock, Int. J. Numer. Anal. Meth. Geomech. (2005)

Petrophysics Specificities of Shales and Claystones

Petrophysics Specificities of Shales and Claystones

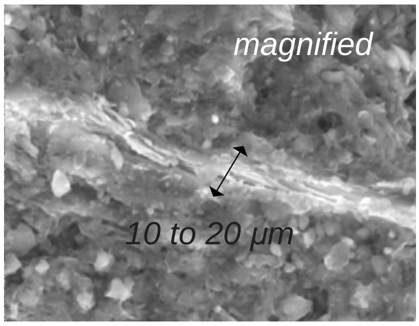
- High content of clay particles:
  - Kaolinite, Chlorite, Illite, Smectite (swelling-shrinkage)



- Micro to nano-porosity:

– Huge surface effects strong molecular bond (double layer theory)

– Almost no free water (extremely low hydraulic conductivity # 10^{-20} m^2)



Pit falls to avoid:

– H-M coupling with Biot theory (few Hertzian contacts)

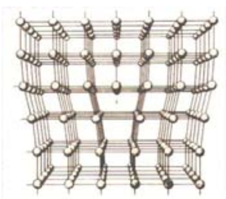
– Little suction because of cavitation

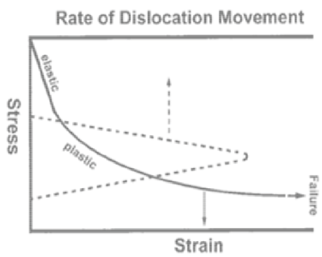
Petrophysics Specificities of Shales and Claystones

- Petro-Fabric :

– Heterogeneities (polycrystal)

– Crystal lattice: strong atomic bond (co-valent, ionic…), dislocation



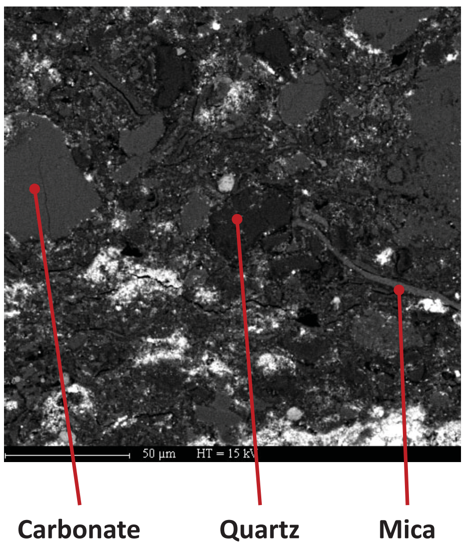


- Anisotropy both in terms of strength and deformability properties (transverse isotropy)

Pit fall to avoid :

Discrete Element Method: not suitable

Bure Argillite



Tests for Mechanical Behavior Characterization

Rocks under Study: Mineral Content and Physical Properties

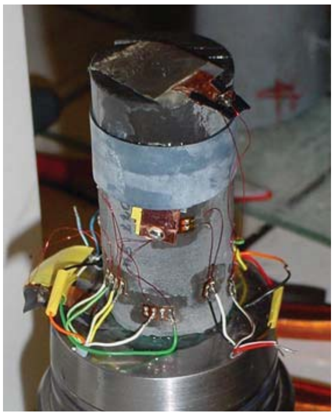
Rock Formations	Geological Periods	Quartz (SiO_2) %	Carbonates ($CaCO_3$) %	Others minerals (Feldspars, micas, pyrite)	Clay Particles	*Kaolinite*	*Chlorite*	*Illite*	*Smectite*	*Interlayers Illite/ Smectite*
Bure Argillite	Callovo - Oxfordian	20 - 30	20 - 33	5	40-45	*10*	*20*	*40*	*-*	*30*
Tournemire Shale	Toarcian	19	15	11	55	*28*	*3*	*16*	*-*	*8*
Mont d'Or Claystone	Jurassic	10	65	-	25	*30*	*15*	*40*	*15*	*-*

	Density kN/m^3	Porosity %	Water content %	Saturation degree %	UCS MPa	Average Moduli GPa	Sonic velocity P wave Max m.s^{-1}	Anisotropy (P-wave velocity)
Bure Argillite	23.7	15.5	5.9	87 %	27-29	5-6	3820	10 %
Tournemire Shale	24.0	8.9	3.4	95 %	35-38	21-27	4225	30 %
Mont d'Or Claystone	25.3	6.4	1.6	63 %	50-80	18-25	4300	16 %

Fabre, G., Pellet, F., Creep and time-dependent damage in argillaceous rocks, Int. J. Rock Mech. Mining Sci,. (2006)

Mechanical Tests for Rocks Behavior Characterization

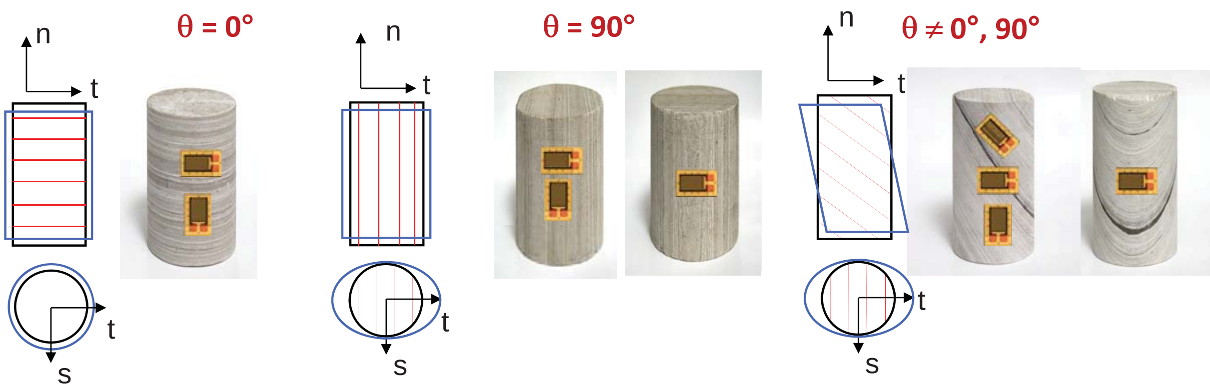
- **Determine the overall time-dependent mechanical properties at the scale of a rock specimen**
  - Compression tests with different rates of loadings
  - Creep compression tests
  - Relaxation tests



H = 80 mm
ϕ = 40 mm

Intrumentation for Transverse Isotropic Specimens

Specimen deformation (strain tensor) :



$$\varepsilon = \begin{pmatrix} \varepsilon_{ss} & 0 & 0 \\ 0 & \varepsilon_{ss} & 0 \\ 0 & 0 & \varepsilon_{nn} \end{pmatrix}_{(s,t,n)}$$

Transversal: parallel to the plane

Axial

$$\varepsilon = \begin{pmatrix} \varepsilon_{ss} & 0 & 0 \\ 0 & \varepsilon_{tt} & 0 \\ 0 & 0 & \varepsilon_{nn} \end{pmatrix}_{(s,t,n)}$$

Transversal: perpendicular to the plane

Distorsion

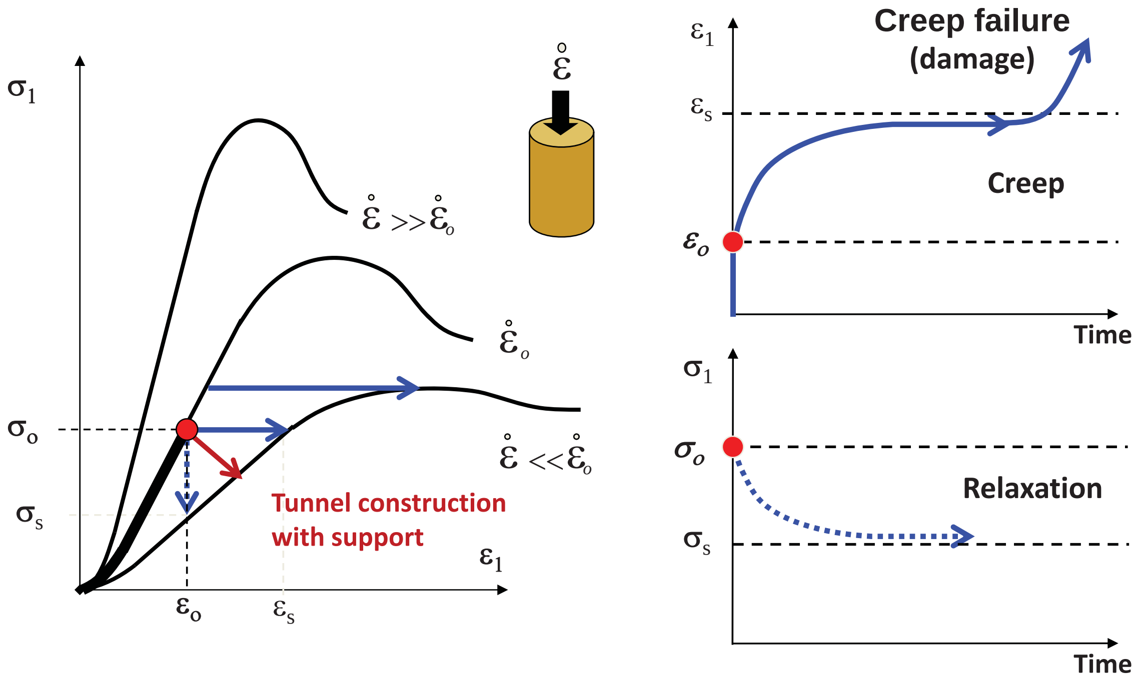
$$\varepsilon = \begin{pmatrix} \varepsilon_{ss} & 0 & 0 \\ 0 & \varepsilon_{tt} & \varepsilon_{tn} \\ 0 & \varepsilon_{nt} & \varepsilon_{nn} \end{pmatrix}_{(s,t,n)}$$

$$\varepsilon vol = \varepsilon ss + \varepsilon tt + \varepsilon nn$$

N. Gatelier, F. Pellet, B. Loret (2002), Mechanical damage of an anisotropic rock under cyclic triaxial tests, Int. J. Rock Mech. Min. Sc.

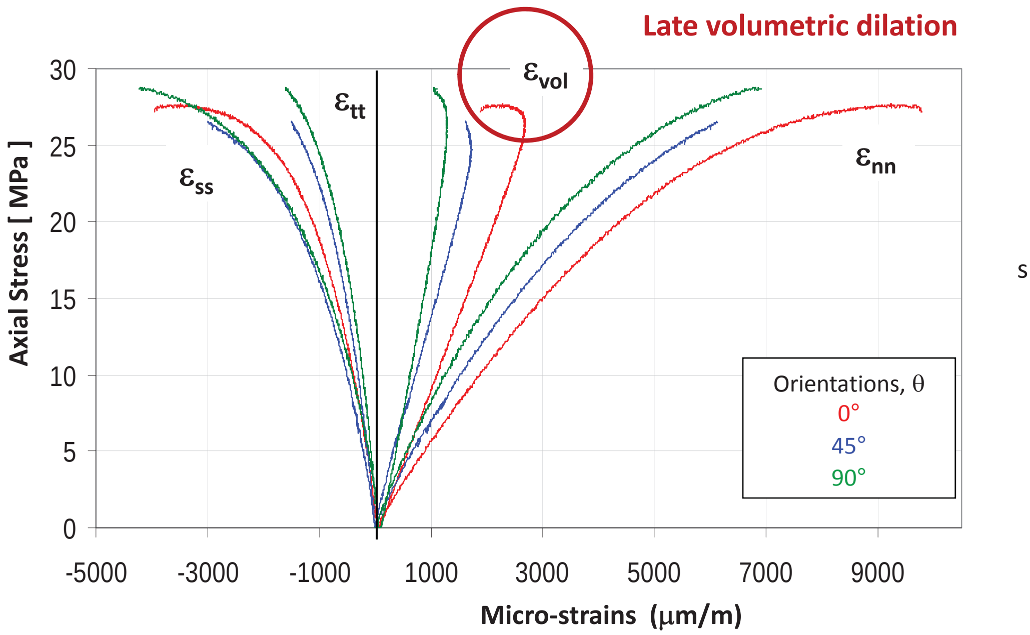
Time-dependent behavior of rocks

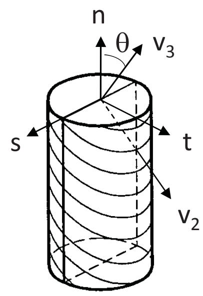
The effect of the rate of loading in compression tests



Monotonic Compression Test on Bure Argillite

Influence of the Structrural Anisotropy (loading rate : $10^{-6}.s^{-1}$)

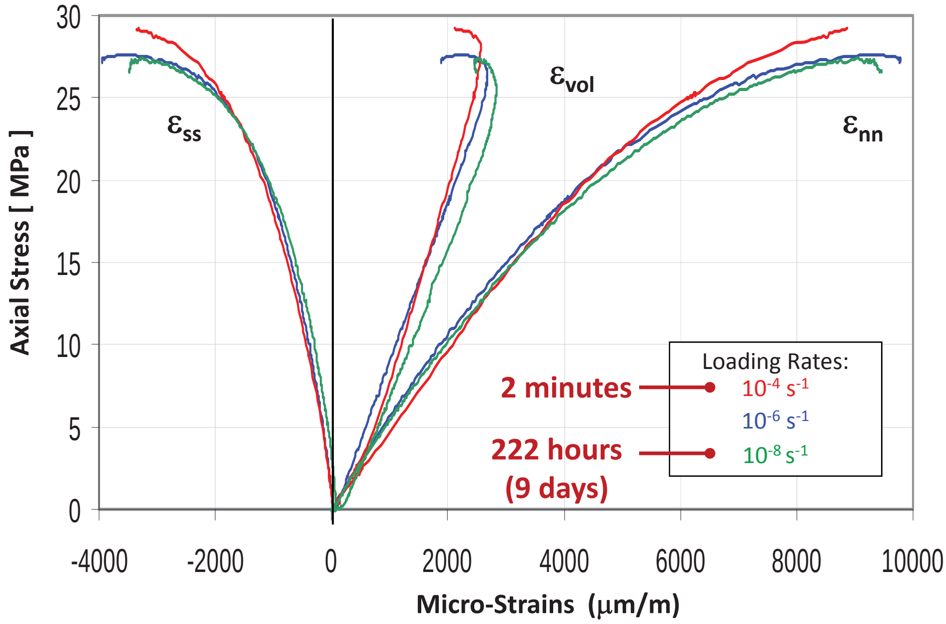




G. Fabre, F. Pellet (2006), Creep and time dependent damage in argillaceous rocks, Int. J. of Rock Mech. and Mini. Sci.

Monotonic Compression Test on Bure Argillite

Influence of the rate of loading (θ = 0°)



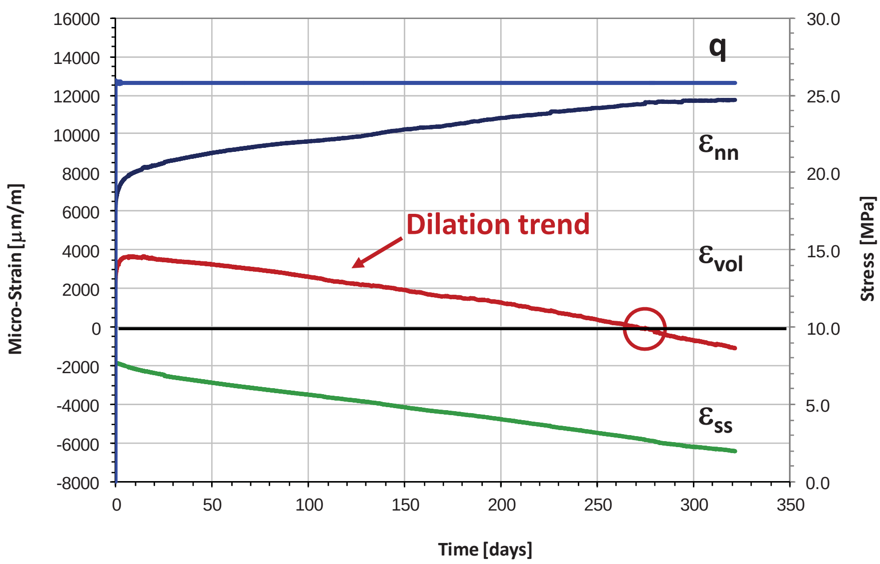
10^{-4} s^{-1}

10^{-6} s^{-1}

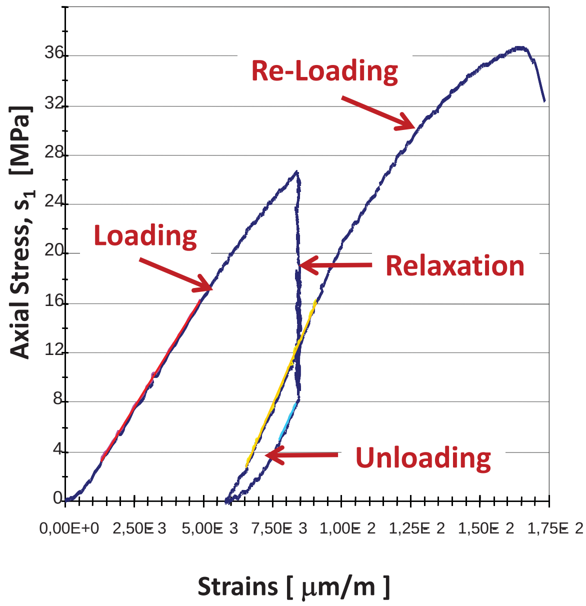
Long Duration Creep Tests in Compression

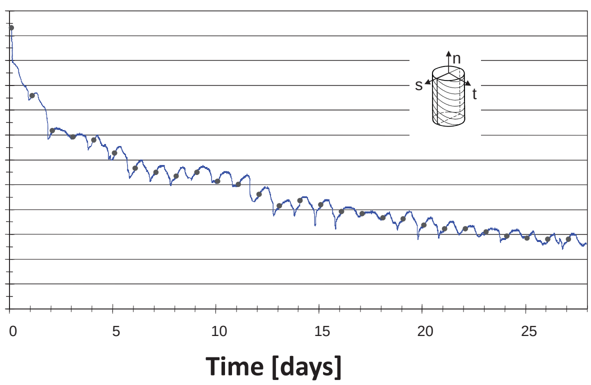
Bure Argillite (θ=0°)

q = 25.8 MPa # 0.9 UCS (27-29 MPa)

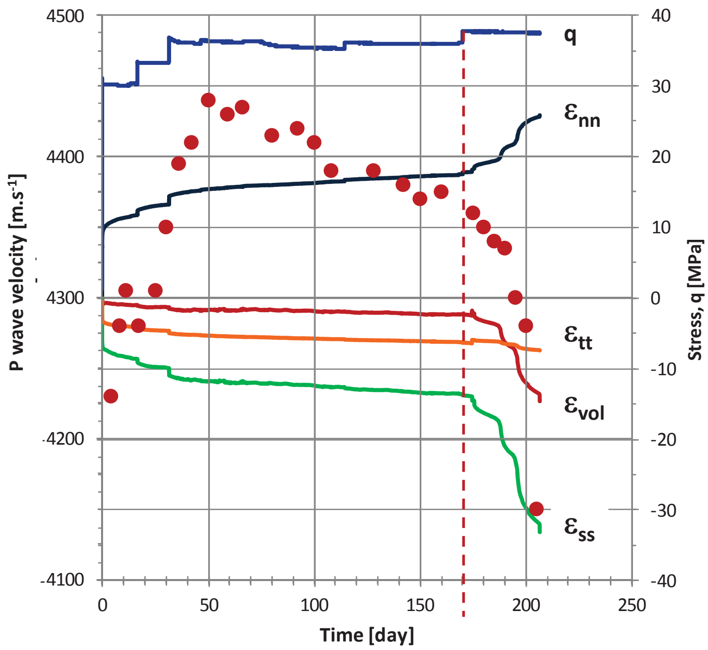


Monotonic Compression Test and Relaxation Stage on Bure argillite





Multi-Stage Creep Tests in Compression on Tournemire Shale

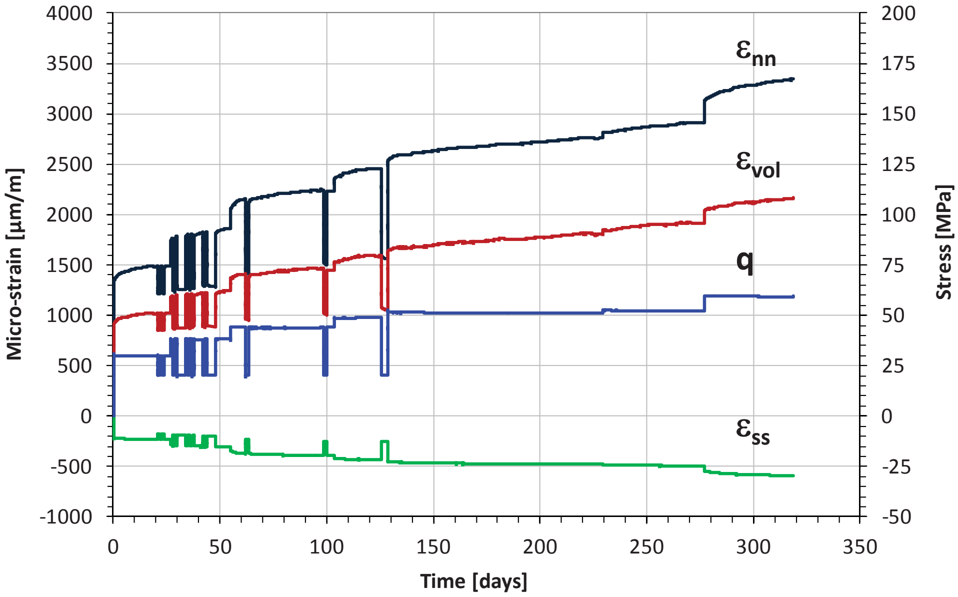


UCS =35-38 MPa; θ= 90°

F. Pellet, G. Fabre (2007), Damage evaluation with P-wave velocity measurements during uniaxial compression tests on argillaceous rocks, Int. J. Geomechanics,(ASCE)

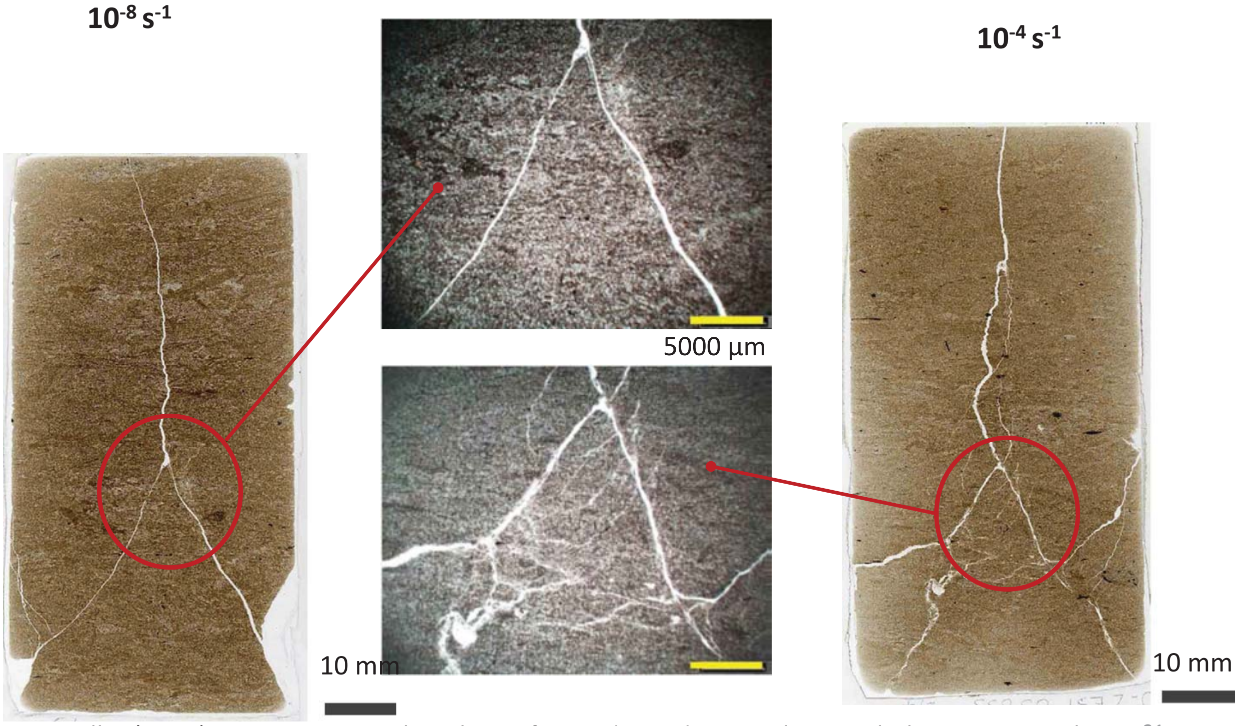
Oligocyclic Creep Test on Mont d'Or Claystone

6 Loading Stages : from 30 to 55 MPa: Unloading down to 20 MPa



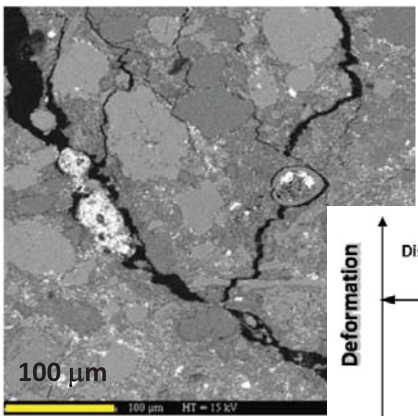
Micro-Structural Analysis of Cracking in Shale

Micro-Structural Analysis of Time-Dependent Cracking in Bure Argillite

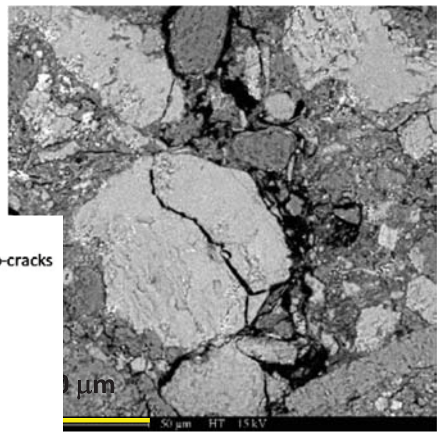


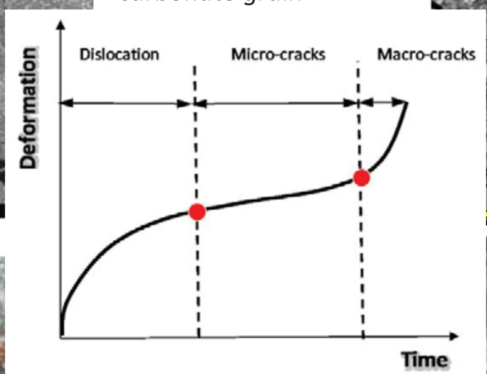
F.L. Pellet (2013), Micro-structural analysis of time-dependent cracking in shale, Env. Geotechnics

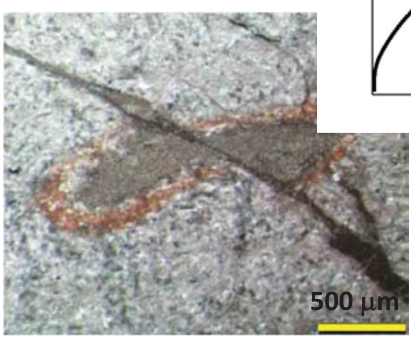
SEM Photographs



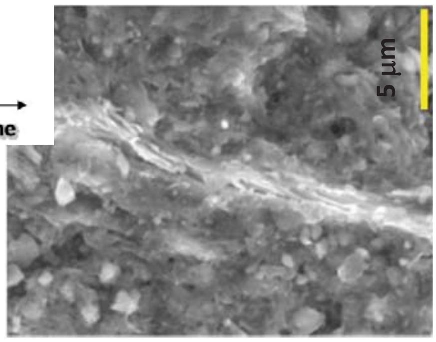
Macro-crack in clay matrix and debonding of quartz and carbonate grain







Micro-crack in clay matrix with re-orientation of the clay platelet along micro-shear planes



Concluding Remarks

- **Petrophysics consequences:**
  - Shales and claystones are **heterogeneous** poly-crystalline rocks, having a high content of clay with micro-pores.
  - At a meso-scale, they are **anisotropic** (transverse isotropic) and exhibit a marked **time-dependent** behaviour.
- **Mechanical Tests :**
  - Creep tests with relaxation tests and strain rate controlled compression tests are necessary to determine the parameters of **any rate dependent models**
  - Prior testing, **physical properties** need to be accurately determined (including sonic velocities)
- **Micro-Structural Analysis of Cracking in Shale**
  - Micro cracking patterns depend on the rate of loading **(energy dissipation)**
  - Micro cracking patterns are also driven by the rock petro-fabric. SEM analysis on thin section **are required** even if others means could also provide good insights (X Ray Tomography)

Final Remarks

- **Keep in mind !**

  - Lab tests results obtained on specimens give you an **order of magnitude** (upper bound) of the mechanical properties of the rock mass (scale effect, discontinuities, other heterogeneities)
  - In situ tests (including geophysics) and monitoring of the underground opening help **to better constrain the mechanical properties** of the rock mass for the numerical analysis (inverse analysis, uncertainties assessment)

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Thank you for your attention !

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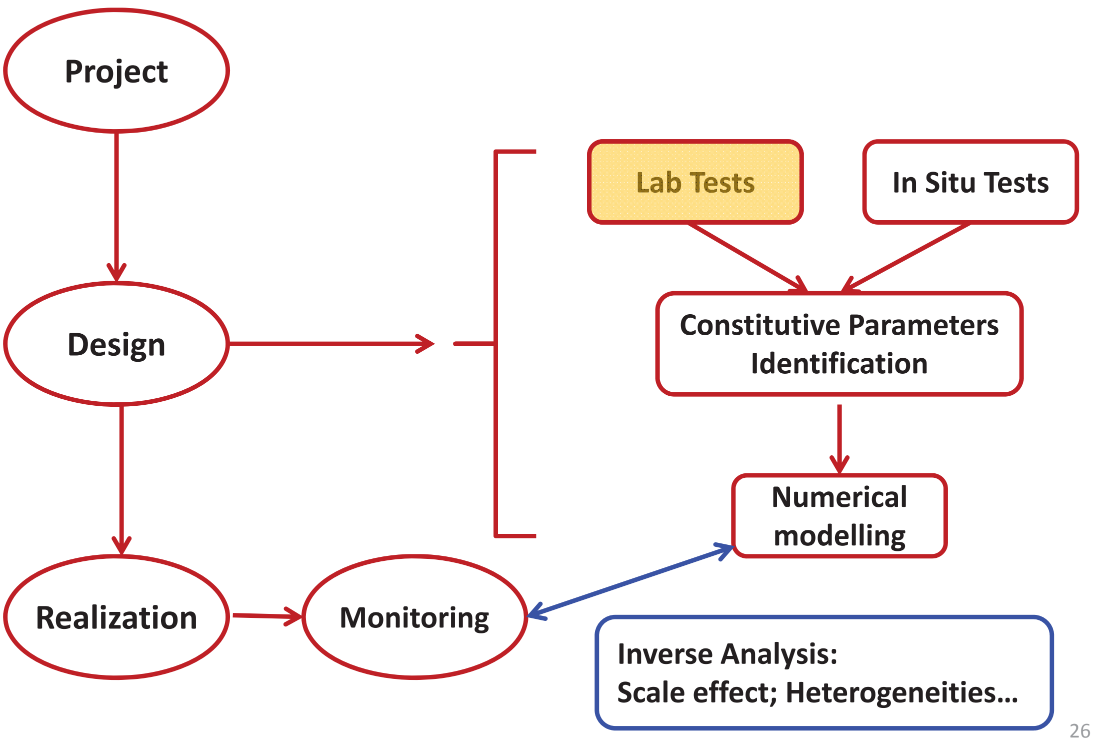
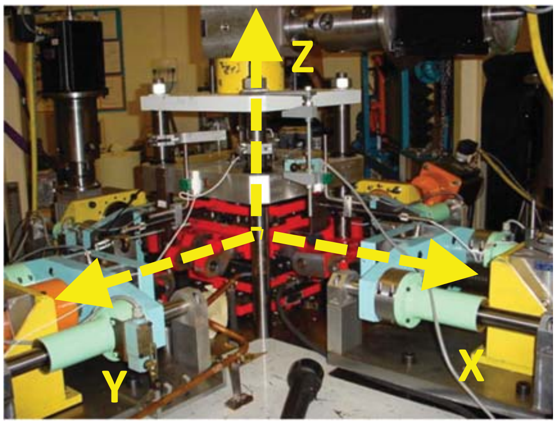
Simplified Flow Chart for the Design of

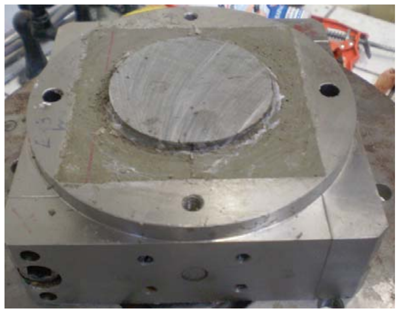


Shear Strength of Clay Rock Discontinuities

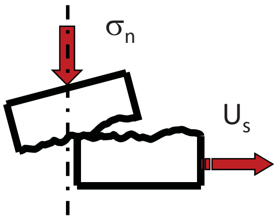
BCR3D : Servo-Controlled Direct Shear Equipment



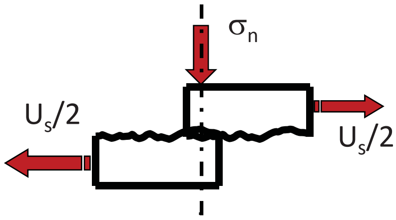
Bure Argillite Specimen



Stress and displacement servo-controlled in the 3 directions , Fluid injection : Control Pressure Volume



Conventional shear box : rotation



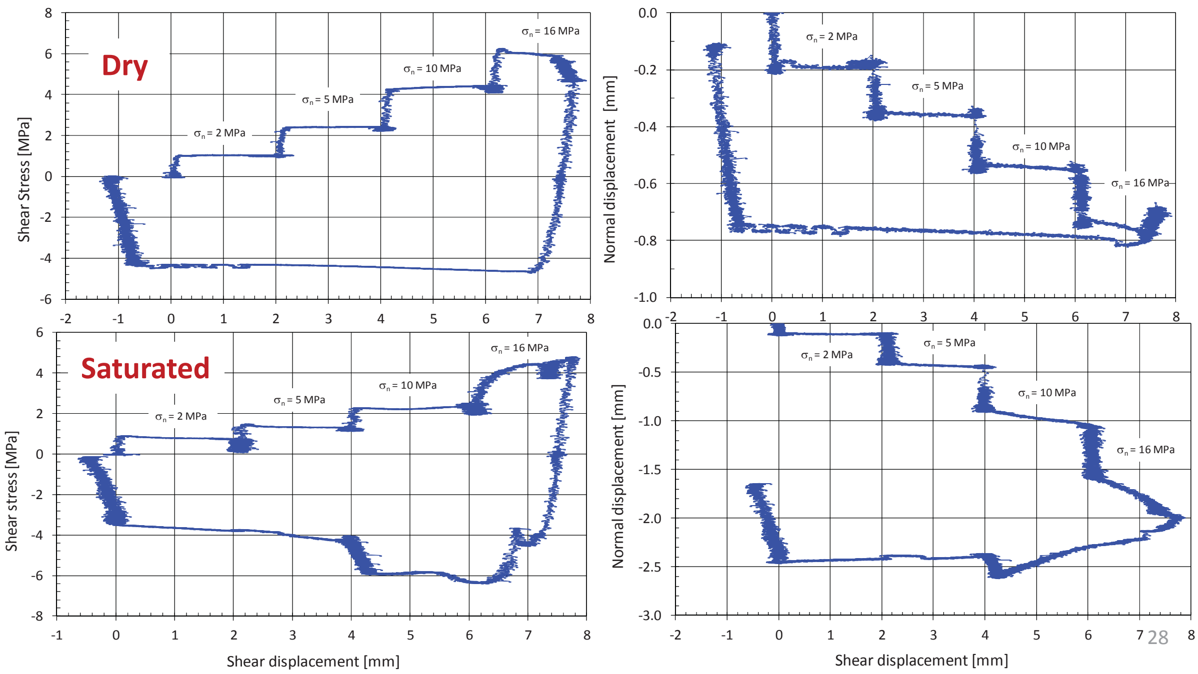
BCR3D shear box : no rotation

Shear test on dry and saturated discontinuities

Constant Normal Load (CNL), shearing rate of 0.05 mm/s

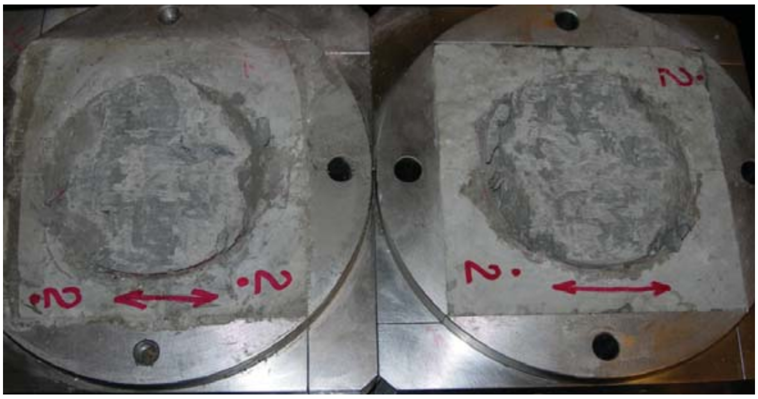
Shear stress - shear displacement

Normal displacement - shear displacement

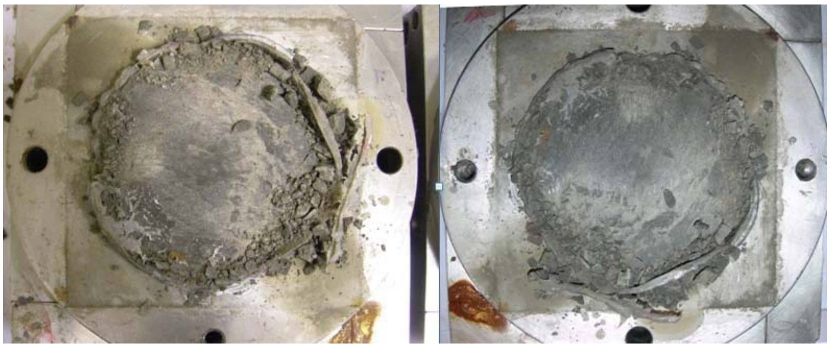


Photos of the discontinuities after testing

Dry discontinuity



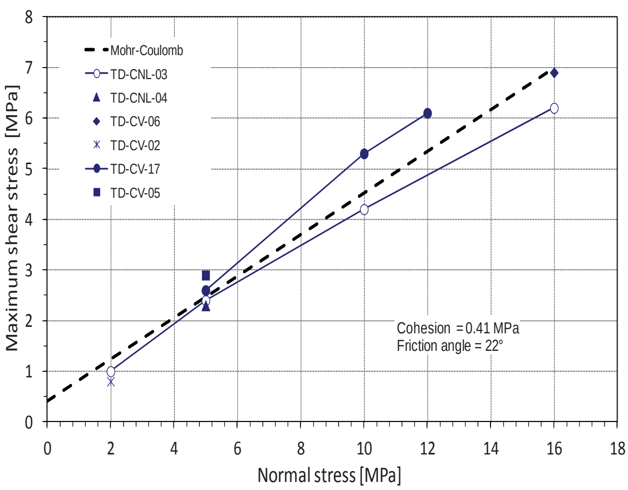
Saturated discontinuity



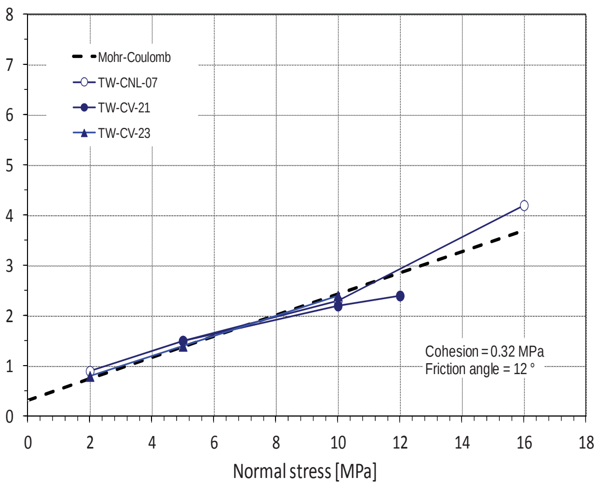
Left: lower part **Right: upper part**

Normal stress versus maximum shear stress

Dry discontinuities



Saturated discontinuities



F.L. Pellet, M. Keshavarz, M. Boulon (2013), Influence of humidity conditions on shear strength of clay rock discontinuities, Engineering Geology.