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Old geomechanics for new energy: the importance of rock fluid(s) interaction

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Outline

- Motivation
- Examples of time and fluid dependent behaviour
- The embarrassing paradox of effective stress
- Theoretical framework
- Numerical modelling
- Concluding remarks

Acknowledgements: C. Sorgi, H.D. Nguyen, G. Priol, J.M. Pereira, EU Research Framework, INERIS … and many others

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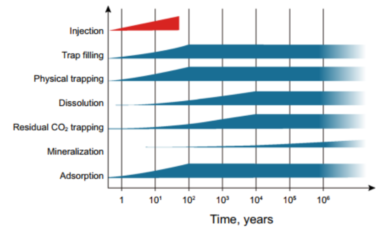
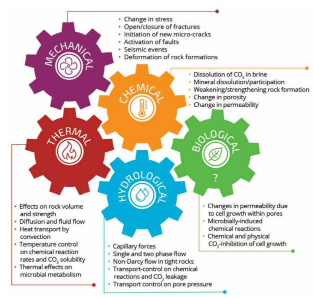
Motivation

- New energy applications (e.g. CO_2, H_2 storage, geothermal) involve pervasively multiphase coupling
- Long time scale are frequently required for analysis
- Coupled processes are often disregarded in O&G operations
- To assess the impact of coupled time dependent processes a rigorous theoretical framework is required



Metz et al. (2005), IPCC (2007)



Newell & Ilgen (2018) - Overview of Geological Carbon Storage (GCS)

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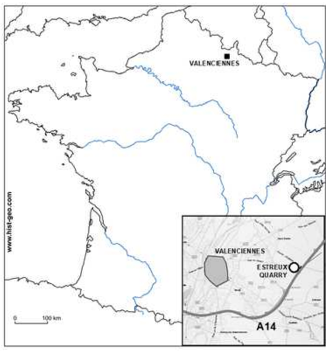
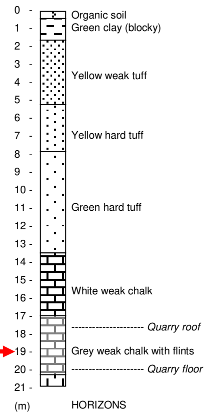
Non energy related case: shallow mine chalks



Sorgi (2004), De Gennaro et al (2003)



Compaction and subsidence in oil reservoir chalks

78m water depth, 2900m bsl, 150m thick

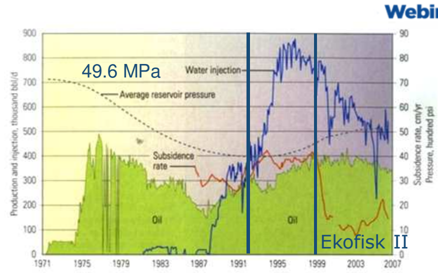
1 billion m^3 of oil originally in place
Production: 1971-2030

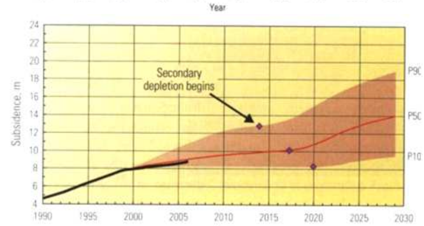
47700 m^3/day of oil

7 millions m^3/day of gas

Late 1980s: full-field water injection

De Gennaro et al (2003), Doornhof et al. (2006)





Water-flooding → Increase of fluid(s) pressure → Biot-Terzaghi mean effective stress decreases

→ Expected : unloading (elastic) and decreasing compaction

→ Observed : increasing compaction and constant subsidence rate !!

Wellbore Damage

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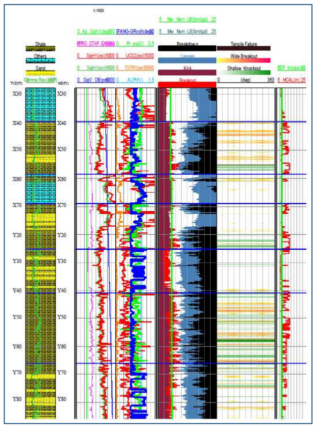

Table 4: Summary of back-analysis of time-dependent wellbore instability events in Wara Shale

Well	Depth (ftMD)	Mud Type	Mud Activity	Mud Weight Used (ppg)	Openhole Duration (Day)	Hole Enlargement (% of Wellbore Diameter)	Calculated Pore Pressure Change After Maximum Exposure Duration		
							Mud Pressure Penetration Pore Pressure Change (psi)	Chemical Potential Mechanism Pore Pressure Change (psi)	Total Pore Pressure Change (psi)
A1	X22	$CaCl_2$ Polymer (15.8%$CaCl_2$)	0.89	9.7	4	4.7%	257.1	-88.5	168.7
A1	X37	$CaCl_2$ Polymer (15.8%$CaCl_2$)	0.89	9.7	4	8.2%	237.6	-103.0	134.6
A2	X58	Bentonite (3.5% NaCl)	0.98	9.4	3	15.0%	138.4	330.7	469.0
A2	X59	Bentonite (3.5% NaCl)	0.98	9.4	3	34.0%	131.8	330.7	462.5
A2	X42	Bentonite (3.5% NaCl)	0.98	9.4	3	7.0%	287.2	285.7	572.9
A2	X43	Bentonite (3.5% NaCl)	0.98	9.4	3	40.0%	125.3	203.0	328.4
A2	X44	Bentonite (3.5% NaCl)	0.98	9.4	3	8.4%	172.3	330.7	503.0

Wara Shale Activity: 0.916

Mud Activity > Shale Activity
Water saturation increases in the formation

Positive net change indicates that pore pressure increases with time in the formation → effective stress decreases

Chee et al., 2009 (SPE 126052)

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Salt Creep

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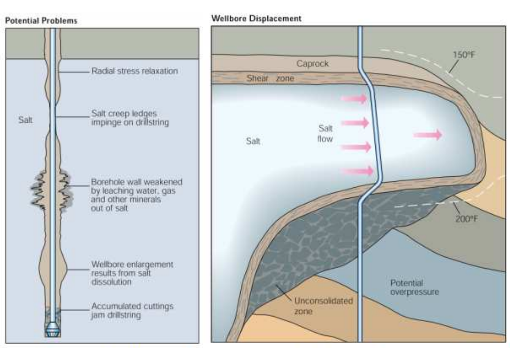
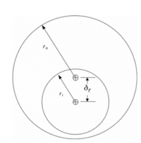
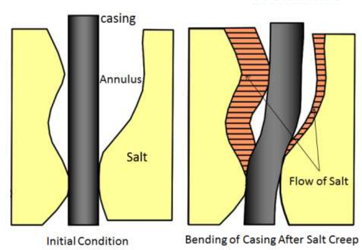


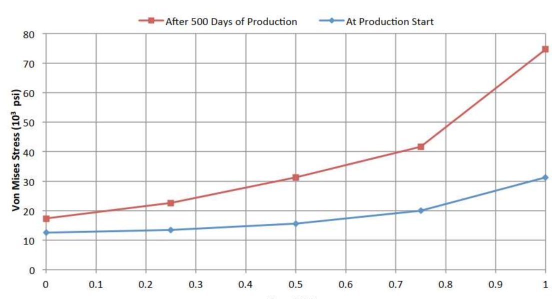
Fig.1 Challenges of drilling and completion in a salt formation (Farmer et al., 1996)

Wang & Samuel, 2013 (SPE 166144)

$$\epsilon = \frac{\delta_r}{r_0 - r_i}$$







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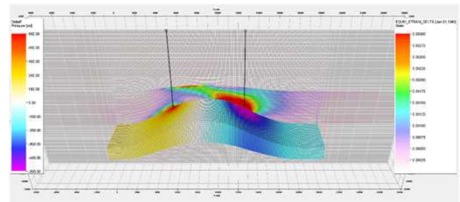
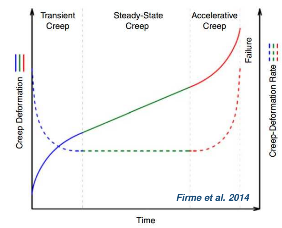
Salt Creep

- Shear stress suppression
  - Linear elastic material model
  - Zero pore pressure or zero Biot
  - Calculate original bulk modulus based on experimental data
  - Calculate new Young's modulus while setting Poisson ratio close to 0.5
  - ➢ Preserve volume changes, while suppressing shear stresses

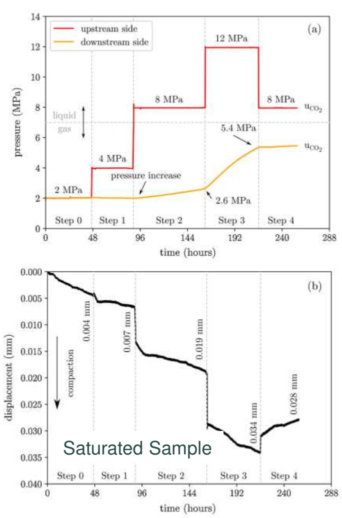


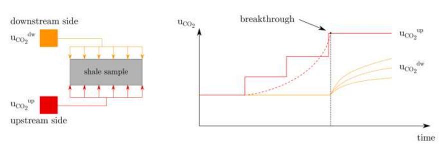
- Apply creep material model
  - Linear elastic material model with power-law creep
  - Zero pore pressure or zero Biot
  - Apply original elastic moduli and creep parameters from lab tests
  - Initialize stress state choosing from different methods
  - ➢ Compute creep strains and corresponding stress change in surrounding



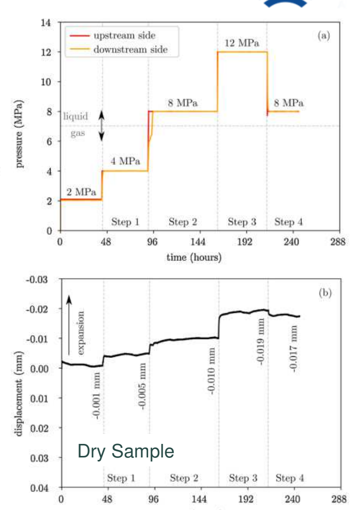
$$\varepsilon_{cr} = A_1\sigma^{n1}t^{m1} + A_2\sigma^{n2}t^{m2}$$

CO_2 Sequestration





- ❑ CO_2 penetrates and propagates in the areas of the material with lower water retention capacity (saturated), without generation of fissures and cracks
- ❑ Results highlight the importance of the water saturation of the caprock material in assessing its sealing capacity and predicting the mechanical response during CO_2 injection



Minardi et al. (2021)

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The embarrassing paradox of effective stress

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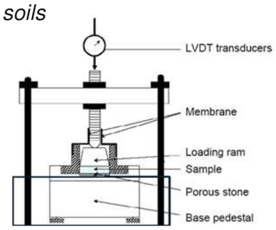
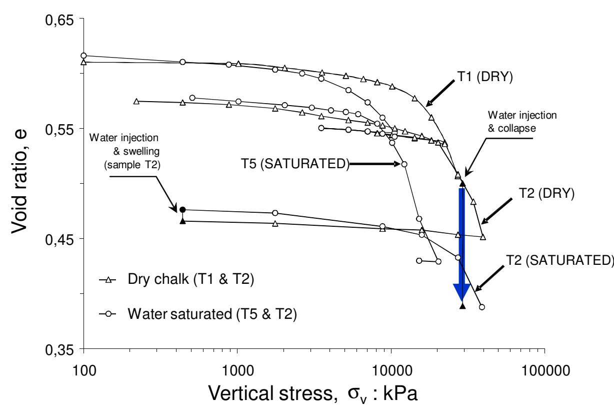
Jennings & Burland (1962)
Limitations to the use of effective stress in partially saturated soils

Bishop & Blight (1963)
Some aspects of effective stress in saturated and unsaturated soils





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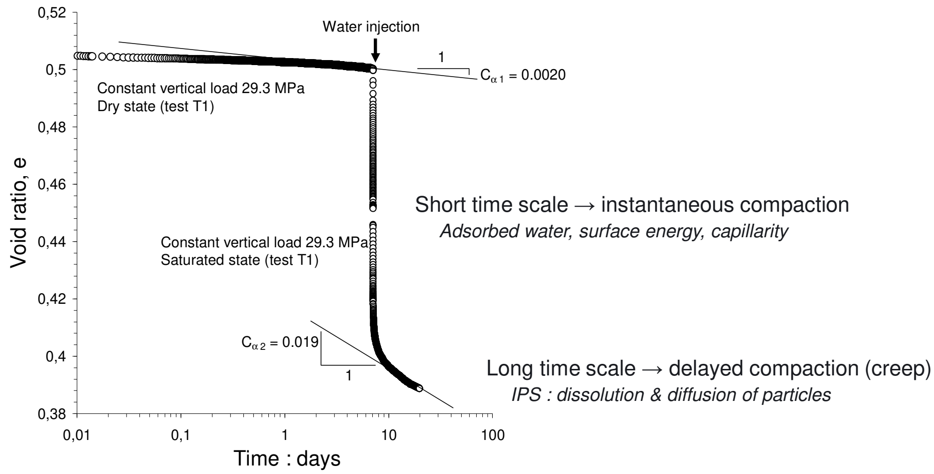
Double Oedometer Test

Time Dependent Hydro-Mechanical Coupling



Estreux chalk : Air - Water

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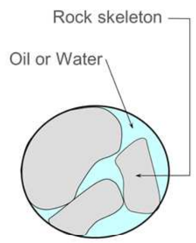
Theoretical Framework



Wetting fluid (w) : WATER

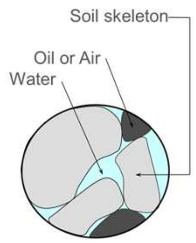
Non wetting fluid (nw) : absent

Material strength encompasses :

- Water activity
- Physico-chemical interactions (e.g. dissolution / precipitation)

Terzaghi – Biot Effective Stress ⟶ $\sigma'_{ij} = \sigma_{ij} - P_{w/nw}\,\delta_{ij}$

- Solid grains incompressible ($\alpha = 1$)
- Energy dissipation due to porosity changes



Wetting fluid (w) : WATER

Non wetting fluid (nw) : OIL or AIR

Material strength encompasses :

- Fluid-Solid interface energy (capillary bonding)
- Water activity
- Adsorption
- Physico-chemical interactions (e.g. dissolution / precipitation)

Bishop's Stress ⟶ $\sigma'_{ij} = \sigma_{ij} - P_{nw}\,\delta_{ij} + S_{rw}(P_{nw}-P_{w})\delta_{ij}$

- Solid grains incompressible ($\alpha = 1$)
- Energy dissipation due to porosity changes and wetting fluid saturation changes
- Porous volumes of Wetting and Non-Wetting fluids deform equally
- P_{nw}-P_{w} is called Suction (s) but often also Capillary Pressure (P_c)

Coleman (1962), Bishop & Blight (1963), Fredlund & Morgenstern (1977), Hassanizadeh & Gray (1980), Lewis & Schrefler (1987), Houlsby (1997), Dangla et al. (1997), Jommi (2000), Coussy (2007), Pereira & Coussy (2010), Pereira et al. (2010)

Theoretical Framework

Combination of two independent stress variables

Dissipation due to porosity changes ⟶ $\sigma_{ij} - P_{nw}\,\delta_{ij} + \mu_1(s, S_{rw})\,\delta_{ij}$

Dissipation due to wetting fluid saturation changes ⟶ $\mu_2(s, S_{rw})\,\delta_{ij}$

For incompressible grains

Net stress $\sigma''_{ij} = \sigma_{ij} - P_{nw}\,\delta_{ij}$ ⟶ this is the classical Terzaghi-Biot Effective Stress

Suction $s_{ij} = (P_{nw} - P_{w})\,\delta_{ij}$ ⟶ this is often called Capillary Pressure (P_c)

Class 1 models	Class 2 models	Class 3 models
$\mu_1 = 0$	$\mu_1 = \mu_1(s)$	$\mu_1 = \mu_1(s, S_{rw})$
$\mu_2 = s$	$\mu_2 = s$	$\mu_2 = s$

choice is a matter of convenience

Gens (1995)

Yielding-Failure in Partially Saturated Rocks

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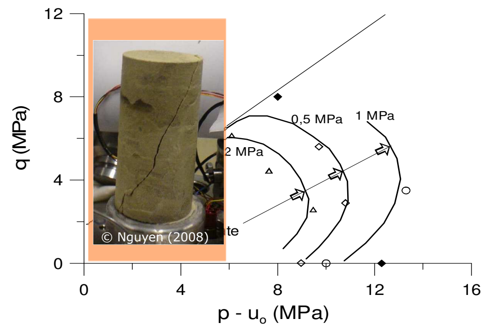
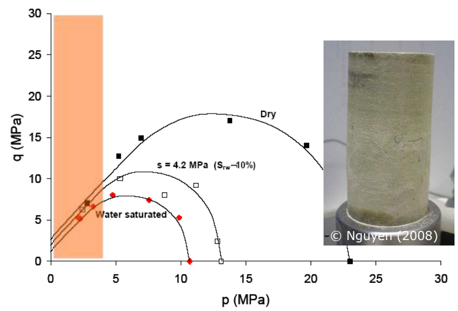


Pasachalk 2 Project (2004)



Nguyen (2009)

- Air or oil act as non-wetting fluids and strength chalks → Hardening depends also on wetting fluid saturation (in addition to plastic strains)
- Samples experience wetting induced compaction (water weakening) → This is a plastic collapse mechanism controlled by S_{rw} or Suction
- Chalk compressibility increases with increasing water content (i.e. decreasing suction) → Increasing compaction & subsidence

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Yielding-Failure in Partially Saturated Rocks

Elastic behaviour

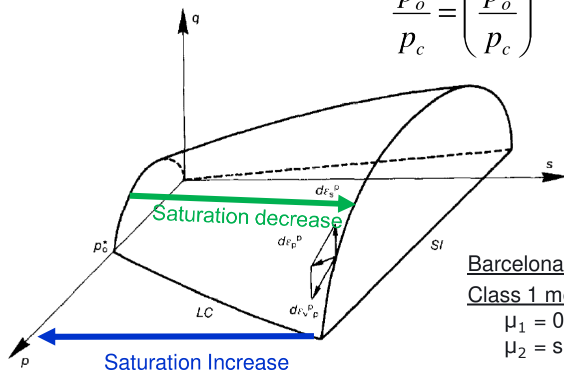
$$d\varepsilon_v^e = \frac{\kappa}{1+e}\frac{dp}{p} + \frac{\kappa_s}{1+e}\frac{ds}{(s+p_a)}$$

Volumetric behaviour

$$d\varepsilon_v = \frac{\lambda}{1+e}\frac{dp}{p} + \frac{\lambda_s}{1+e}\frac{ds}{(s+p_a)}$$

Instantaneous compaction (pore collapse)

$$\frac{p_o}{p_c} = \left(\frac{p_o^*}{p_c}\right)^{\frac{\lambda(0)-\kappa}{\lambda(s)-\kappa}}$$



Barcelona Basic Model (BBM)

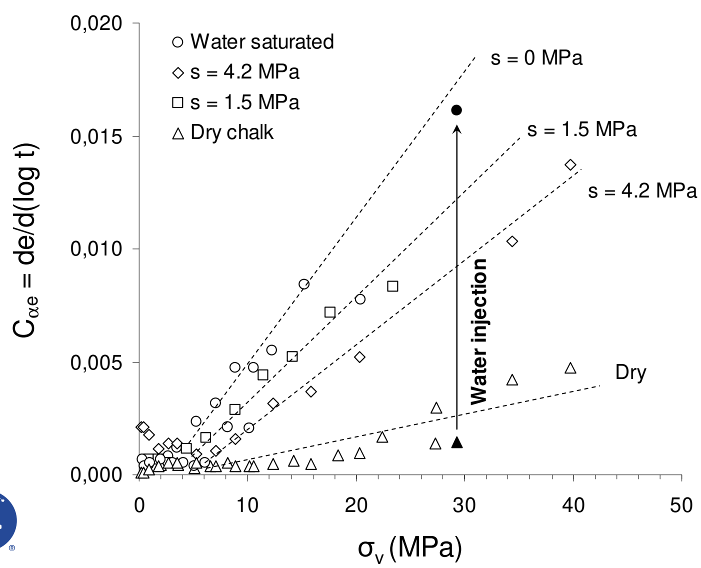
Class 1 model

$\mu_1 = 0$

$\mu_2 = s$

Alonso et al. (1990)

Time Dependent Hydro-Mechanical Coupling



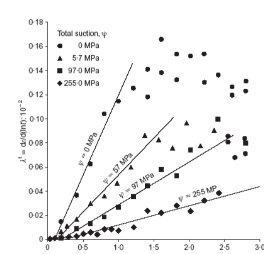


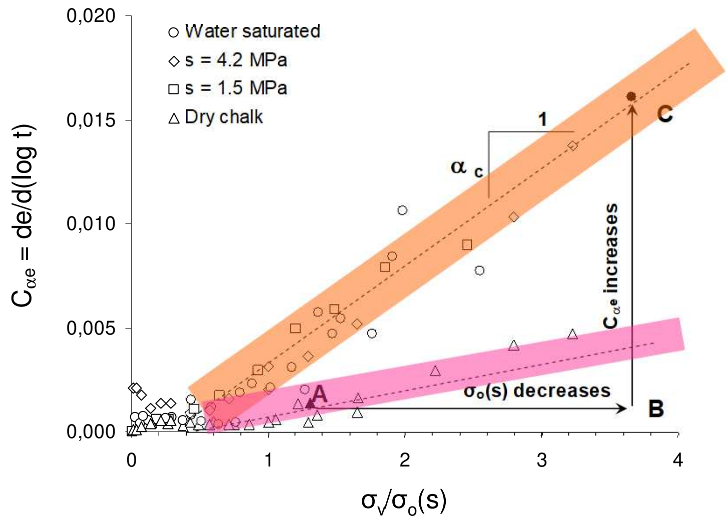
Fig. 6. Time-dependent compressibility index against applied stress for different constant suction values

Oldecop & Alonso, Géotechnique, 2002 & 2007

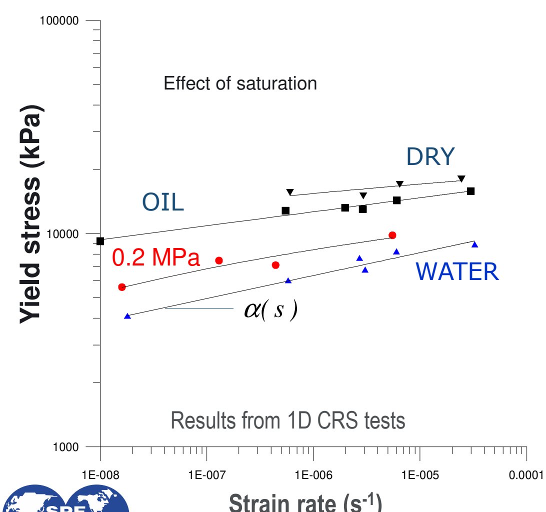
This behaviour is generalized to many geomaterials: creep in partially saturated rockfill, clays, salt, etc.

Time Dependent Hydro-Mechanical Coupling

- Stress values for each test are normalised (divided) with respect to the corresponding yield stress
- This identifies a unique consistent trend
- We can link secondary consolidation, material strength, saturation



Time Dependent Hydro-Mechanical Coupling

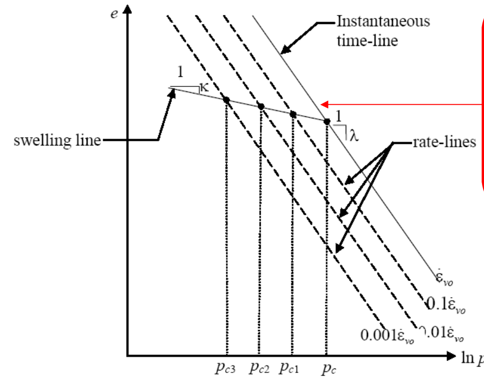


	A	α(s)	Ratio
Water	4.462	0.108	2.44
s=200 kPa	4.516	0.092	2.04
Oil	4.451	0.060	1.33
Dry	4.499	0.045	1

Pasachalk 2 (2004), Priol (2005) PhD, Priol et al. (2007)

Viscoplastic modelling

- Early works from Suklje further developed by Bjerrum for "quick" Norwegian clays collapse have highlighted ISOTACH behaviour
- Interestingly some authors have recently proposed a visco-plastic stress model ("stress relaxation theory") as an alternative for in-situ stress analytical modelling e.g. Sone & Zoback (2014) and Ma & Zoback (2014)
- The ISOTACH behavior has more than one link with the "stress relaxation theory" and it offers a rigorous theoretical framework avoiding pure rheological laws



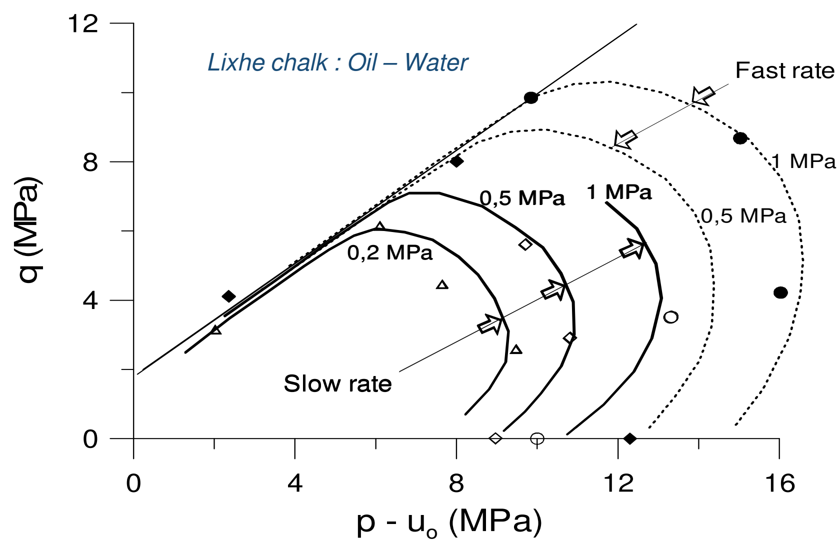
$$\sigma'_{vo} : \varepsilon_{vo} : \dot{\varepsilon}_{vo}$$

The time needed to move from one isotach to another is CREEP

Constant strain rate tests can reduce laboratory time for material characterization

Šuklje (1957), Bjerrum (1967)

Time & Suction Dependency



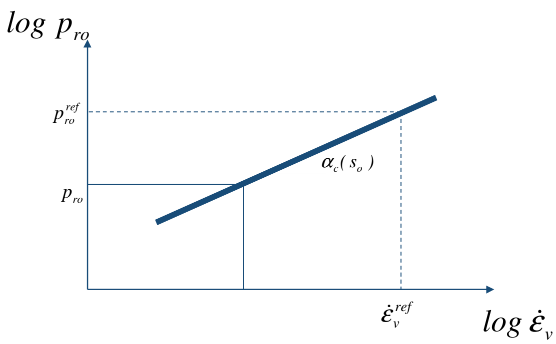
Multiphase Viscoplastic Modelling

Saturation effect ⇒ $f = f(\sigma'', s, \varepsilon^{vp}, \chi)$

Extended plastic hardening $\quad p_o^* = p_o^*(\varepsilon_v^p, \dot{\varepsilon}_v)$

Dragon & Mroz (1979), Lemaitre & Chaboche (1985)

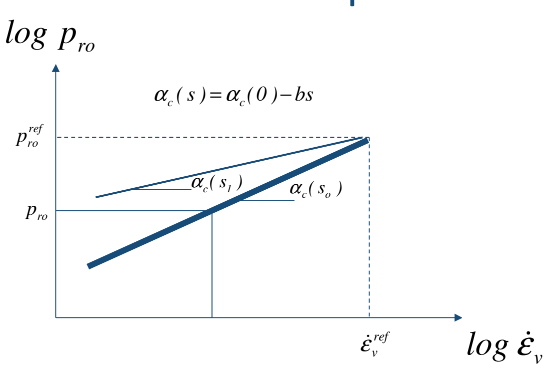
Rate hardening $\quad p_o^* = p_{ro}(\dot{\varepsilon}_v)\exp\left(\frac{1+e}{\lambda-\kappa}\varepsilon_v^p\right)$

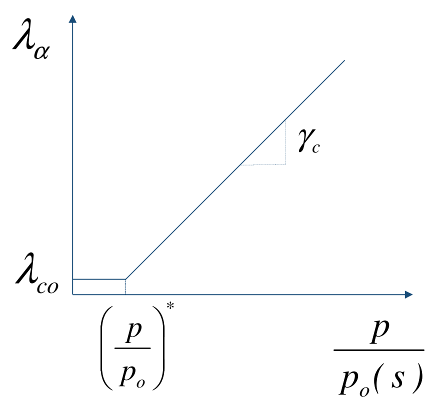


$$p_{ro} = p_{ro}^{ref}\left(\frac{\dot{\varepsilon}_v}{\dot{\varepsilon}_v^{ref}}\right)^{\alpha_c}$$

De Gennaro & Pereira (2013)

Multiphase Viscoplastic Modelling





$$\alpha_c(s) = \frac{\lambda_\alpha(s)}{\lambda(s)}$$

coupling

De Gennaro & Pereira (2013)

Model Results – Rate Dependency

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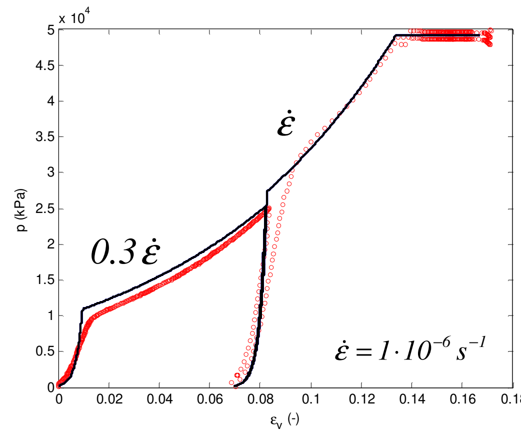
BBM parameters

κ	λ	r	β (MPa^{-1})	p_c (MPa)
0.004	0.15	0.9	0.25	0.01

Rate parameters

$\dot{\varepsilon}_v^{ref}$	p_{r0}^{ref}	$\alpha_c(0)$	b (MPa^{-1})
7	28	0.108	0.043

Lixhe chalk
s = 1 MPa (S_{rw} = 10%)
e_o = 0.7



De Gennaro & Pereira (2013)

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Model Results – Creep

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BBM parameters

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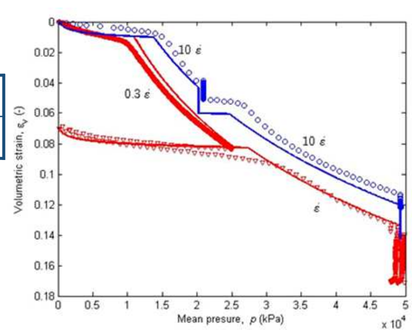

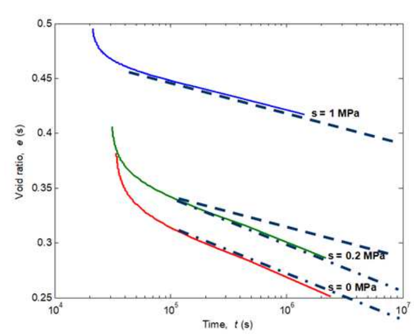

De Gennaro & Pereira (2013)

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Concluding Remarks

- Time and fluid dependent behaviour in rocks can be consistently described by a rigorous theoretical framework (isotach and extended plastic hardening)
- Extension to partial saturation can help addressing more effectively and rigorously phenomena like "water weakening", mud fluid sensitivity without introducing unnecessary uneven assumptions
- Model's parameters can be inferred by standard tests and can be used to identify reliable trends in the case of time dependency
- Existing constitutive modelling and computational methods in geomechanics seldom used in O&G and can be successfully used for new energy applications


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