Desiccation Cracking of Soils

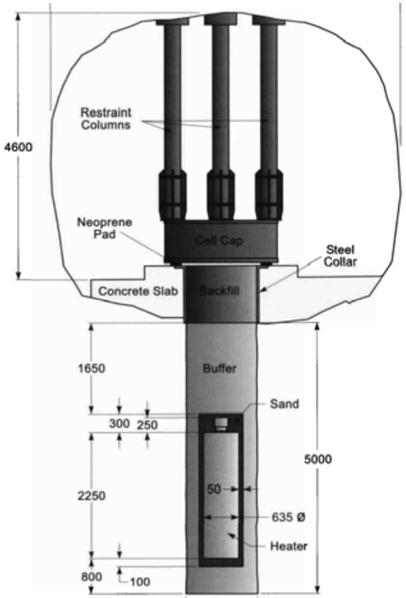
Lyesse Laloui

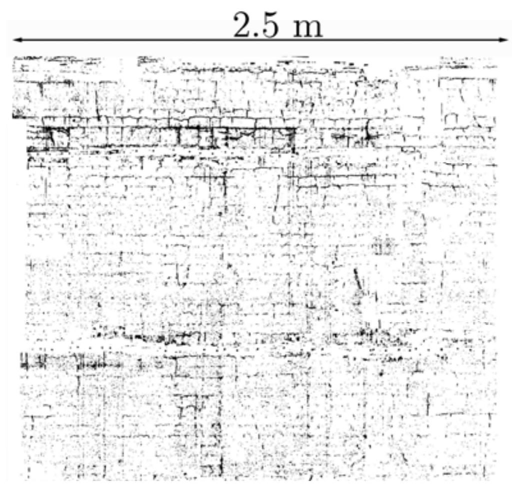
Hervé Péron, Tomasz Hueckel, Liangbo Hu

Ecole Polytechnique
Fédérale de Lausanne
Switzerland

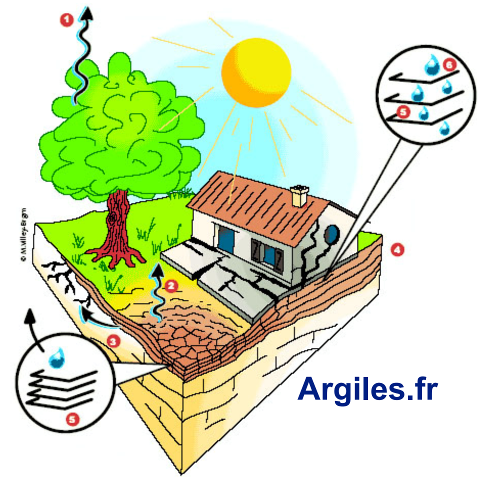
Duke University, NC
USA

The consequences of desiccation cracking

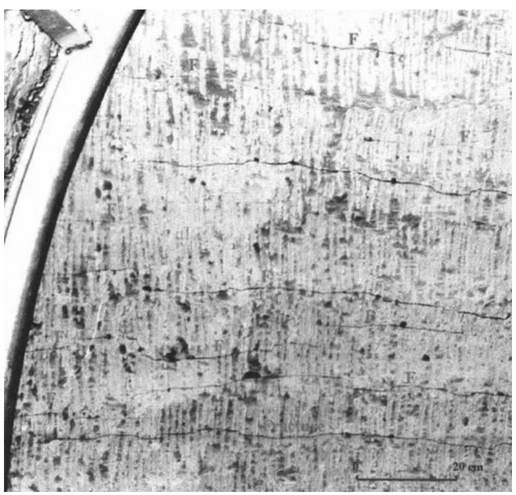




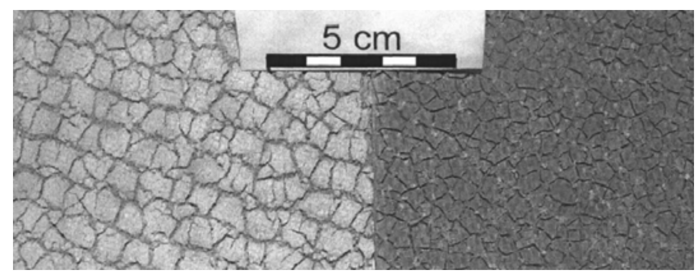
Affects the stability of earthen structures



Dramatic increase of the permeability of engineered clay buffer for nuclear waste storage



… a major challenge in geotechnical engineering.



Dramatic increase of the permeability of landfill clay liner

Scope of the presentation

1. To find out the hypothetical mechanisms (uncertain) and the controlling parameters of desiccation and desiccation cracking.

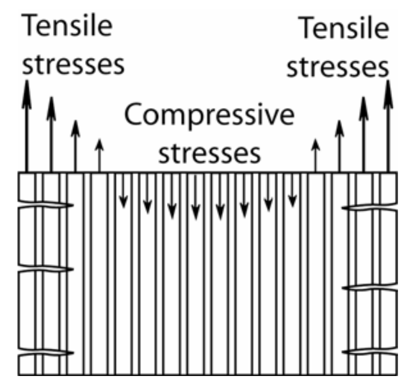
2. To formulate a mechanical constitutive model to predict the conditions for cracking initiation and to propose some tools for a correct modelling of desiccation crack extension.

Basic Processes

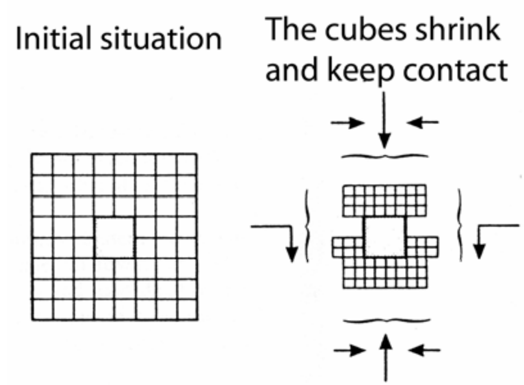
- **Drying = loss of soil liquid evaporated to a drier environment.**
- **Loss (evaporation) of water / suction increase / effective stress increase**
  → mass shrinkage (*free* shrinkage)
- **If shrinkage is constrained, reaction forces arise.**
  tensile stresses are built up → tensile strength is reached
  → desiccation cracks can appear and propagate.
- **Three main causes of shrinkage constraint:**

(1) Boundary restraint

(2) Moisture gradients inside the body



(3) Internal structure



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Experimental characterization and phenomenological study of desiccation cracking process

Presentation of materials (1/2)

- **Bioley silt**
  CM
  Clay = 25 % (with smectite)
  W_L = 32 % / W_P = 17 %

- **La Frasse clay**
  CM
  Clay = 29 % (with smectite)
  W_L = 31 % / W_P = 20 %

- **“Rock powder”**
  CL
  Almost no clay minerals
  W_L = 30.7 % / W_P = 20.3 %

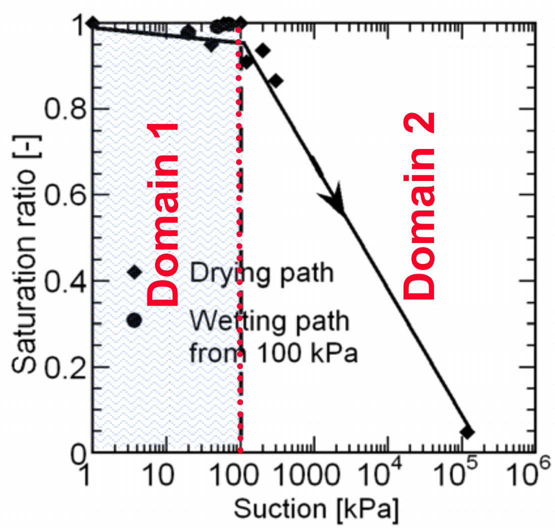
- **Sion silt**
  CL
  Clay = 8 % (with almost no smectite)
  W_L = 25.4 % / W_P = 16.7 %

- **Preparation: saturated slurry**
- **Aim: air bubble removal + no structure**

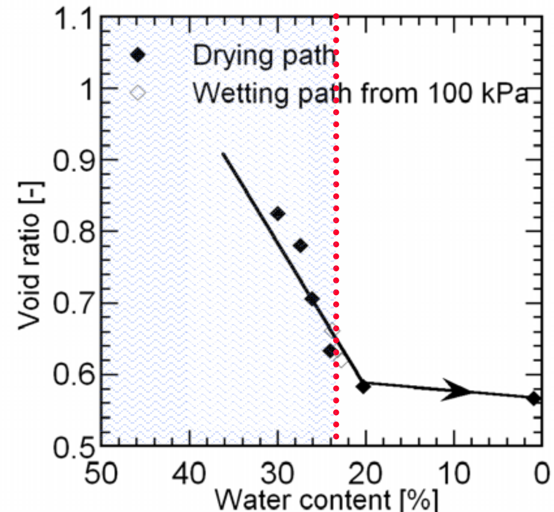
Presentation of materials (2/2)

Water retention properties

WRC determined in pressure extractor (axis translation technique) with zero mechanical stress.

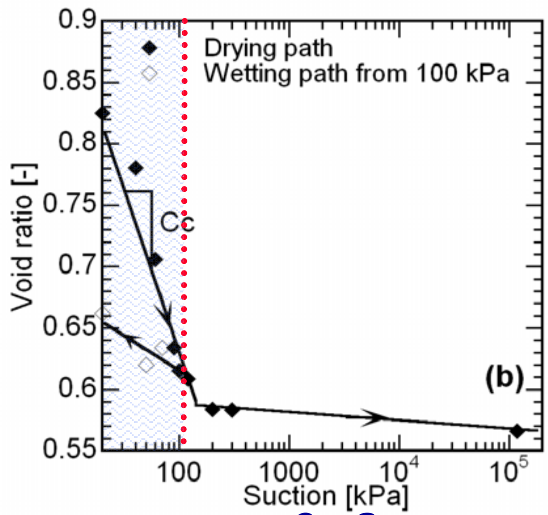


S_r - s

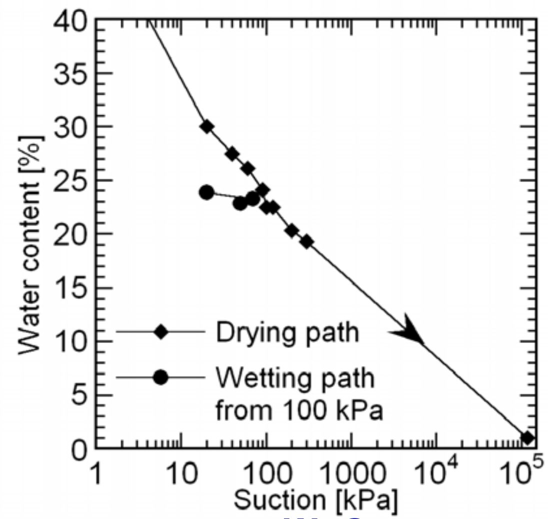


e - w

Domain 1: deformation are mostly irreversible (large during the first drying).
Threshold = shrinkage limit / air entry value
Domain 2: deformation are reversible (very small).



e - s

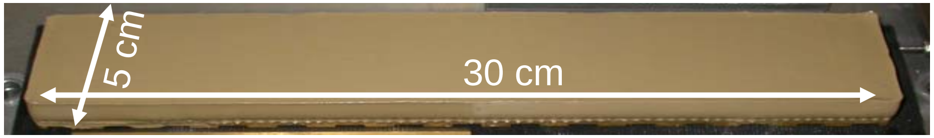


w -s

Geotechnical Testing Journal, vol. 30, N°1, pp. 1-8, 2007

Desiccation test procedures

Free desiccation tests



➢ **Drying of Bioley silty clay cakes without any boundary constraint (Teflon support).**

Measurement of:
- **total water content - weighing**
- **water content repartition - sampling**
- **strains - calipers**

Use of different liquids (water, ethanol solution or ethylene glycol) and different soils (Bioley silt, Sion silt and rock powder).

Constrained desiccation tests

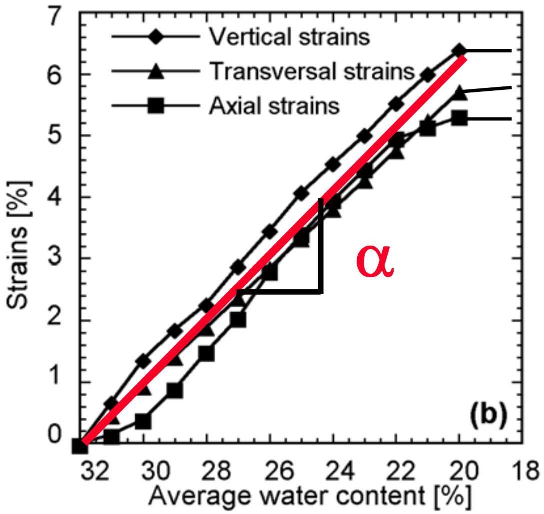
Drying is performed with controlled temperature and relative humidity

➢ **Drying of Bioley silty clay cakes with axial bottom restraint (notches).**

Measurement of:
- **cracking suction – *tensiometer, …***
- **cracking water content - *sampling and weighing,***
- **strains – *calipers,***
- **crack opening – *image analysis.***

Free desiccation test results

Bioley silt + water

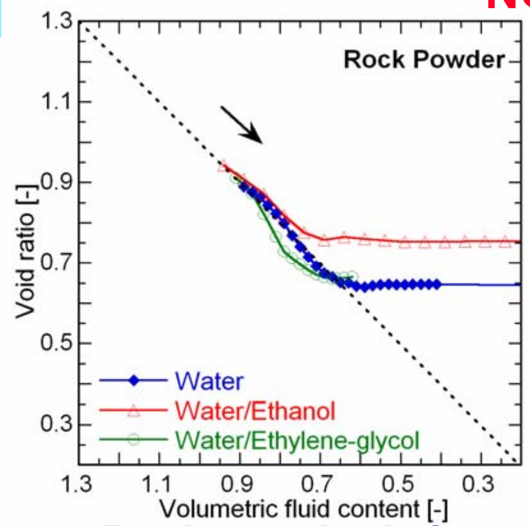


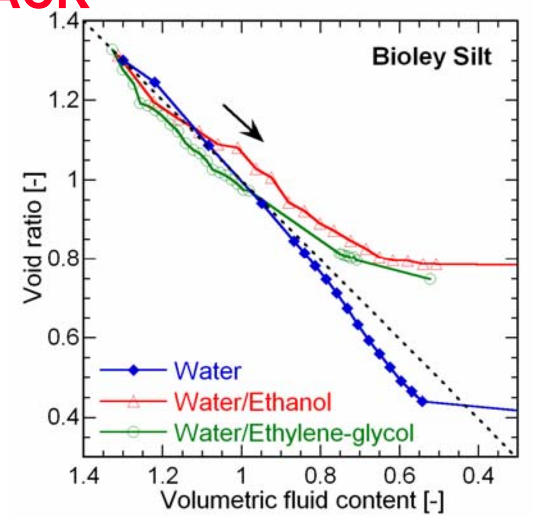
Water content repartition: only small moisture gradients.

No large discrepancy between these tests and WRC with pressure extractor.

- NO CRACK -

Varying soils + liquids





Shrinkage with Bioley silt is higher than with rock powder

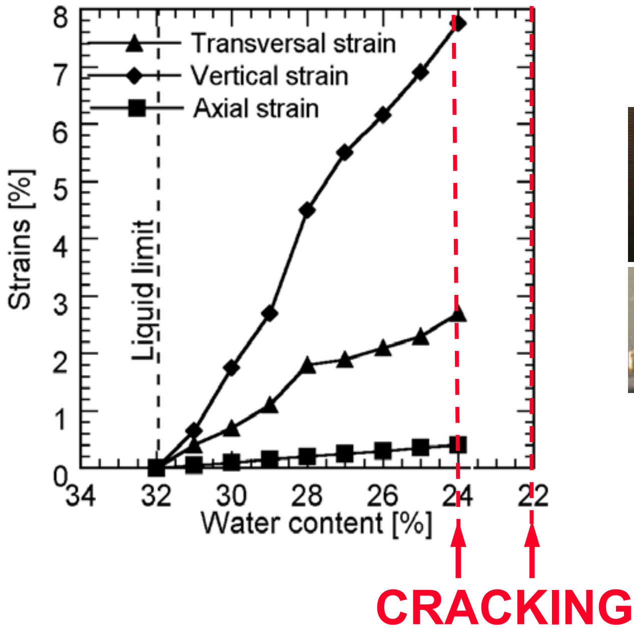
Water involves the largest amount of shrinkage, ethanol the lowest.

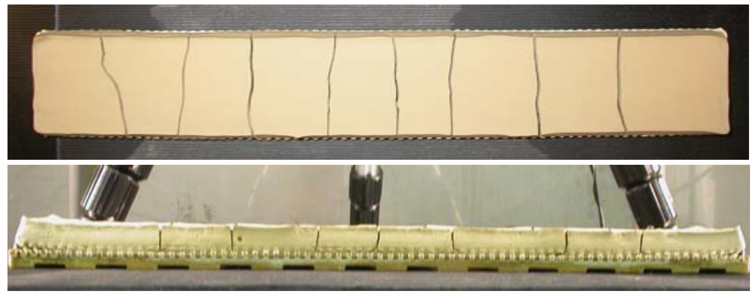
Rock powder is less compressible than Bioley silt.
Clay wetted with alcohol is much less compressible than when wetted with water.

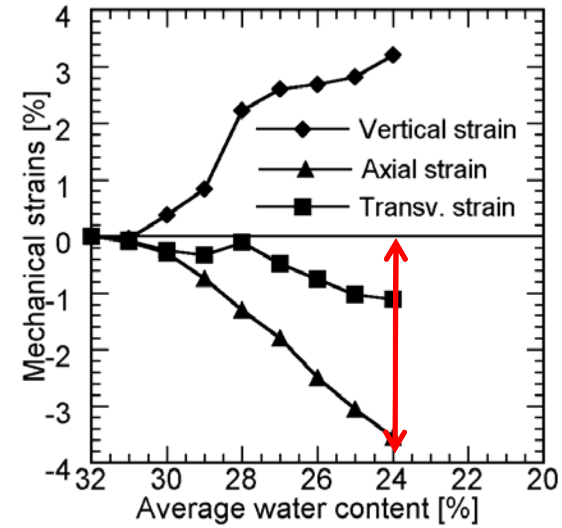
Surface tension plays a major role in the shrinkage process

Constrained desiccation test results (1/2)

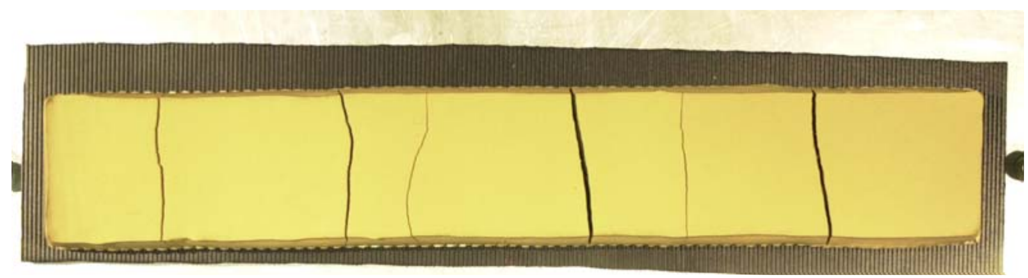
General observations





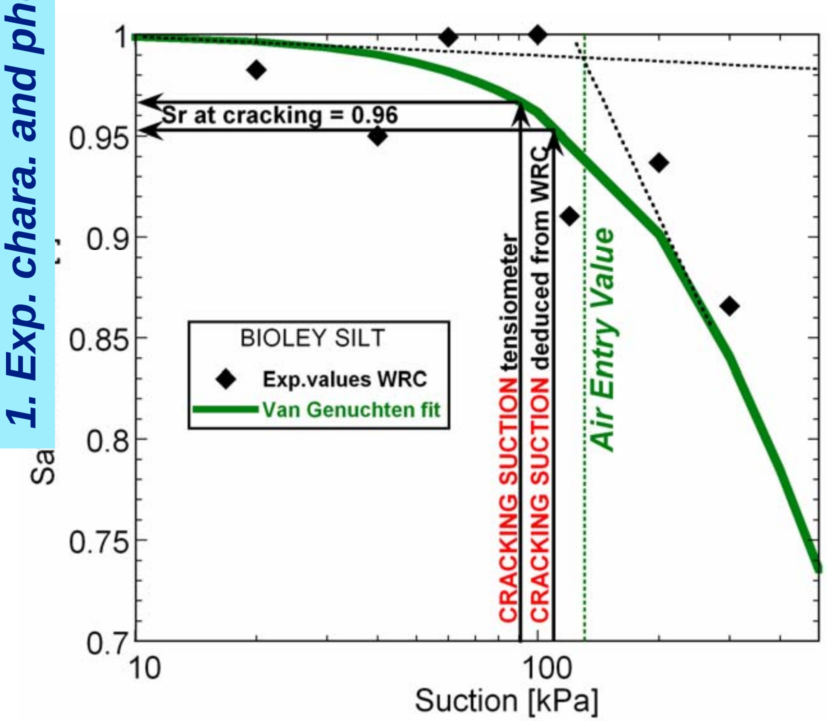


- ✓ **Reproducible pattern of 6-8 parallel cracks perpendicular to the direction of constraint.**
- ✓ **Cracking occurs in a noticeably narrow w range.**

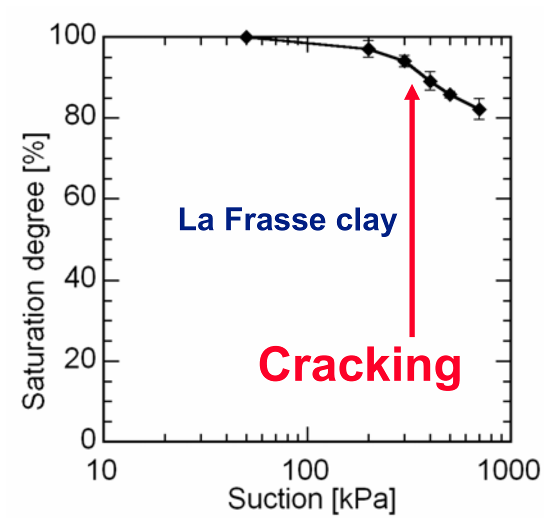


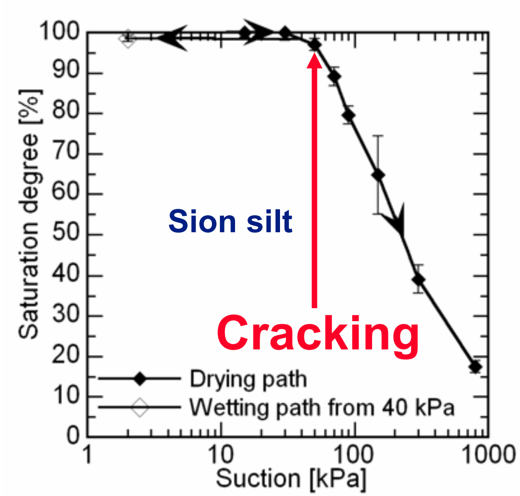
Constrained desiccation test results (2/2)

Suction and saturation ratio at cracking



- **Cracking occurs in Domain 1, close to the air entry value and the onset of desaturation.**





- **Flaws can be attributed to the formation of unsaturated zones ⇒ analogy between this irregularity and a potential crack [Scherer 1990].**

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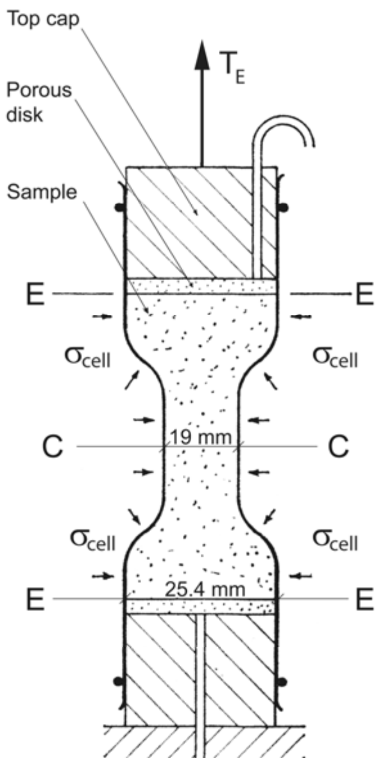
Experimental determination of tensile strength

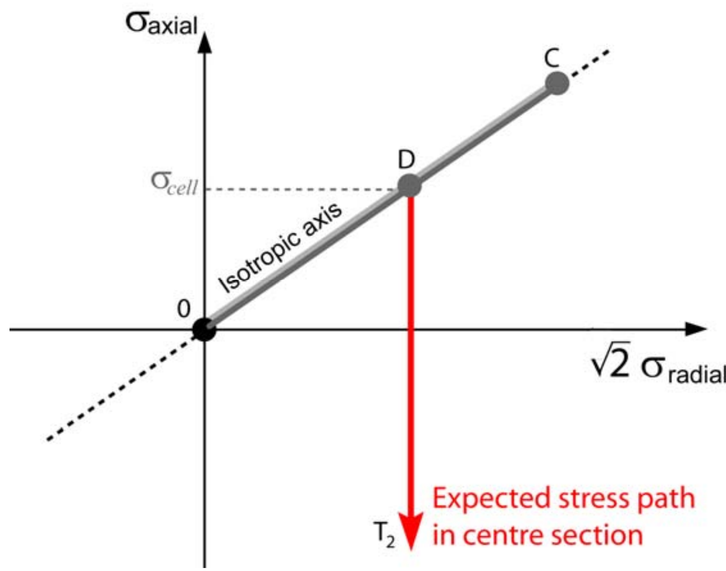
Tests by the "triaxial traction method"

Principle

➢ **Performing extension with an adapted sample shape: creation of a traction in the mid-section.**

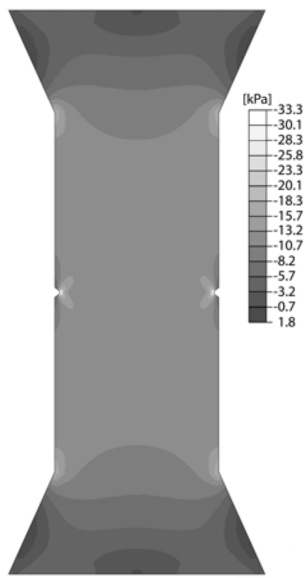


[Bishop and Garga 1969]



Method :

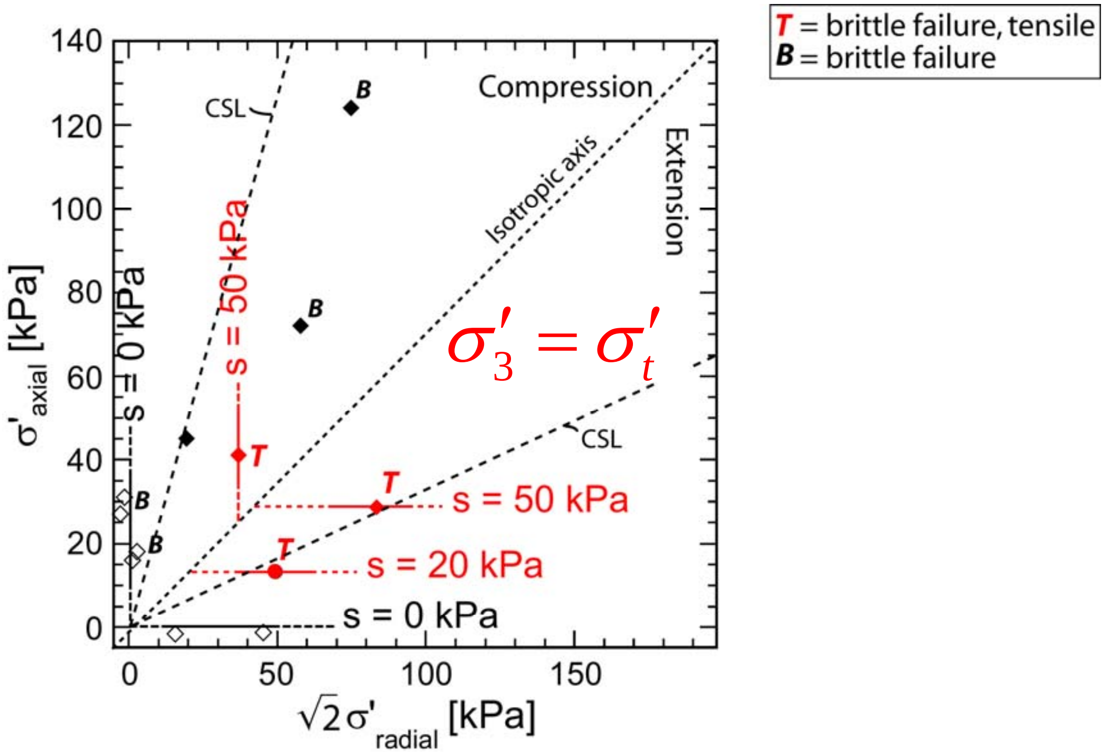
1. **Iso. consolidation OC.**
2. **→ Deconsolidation CD.**
3. **→ Cutting.**
4. **(→Suction imposition).**
5. **→ Extension DT_2.**



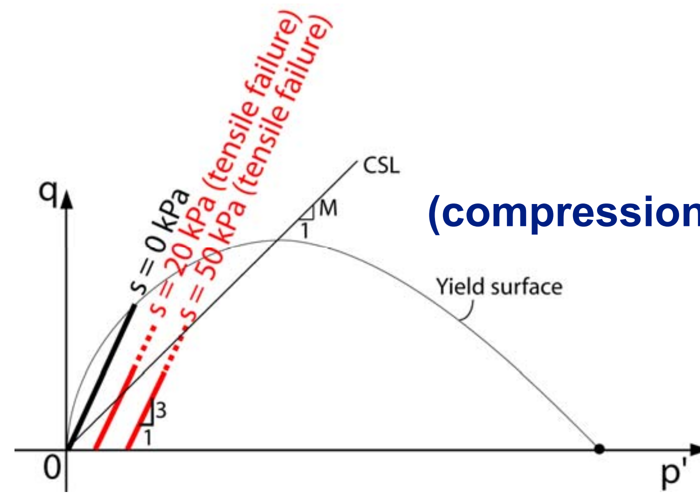
$$\sigma'_{C,\min} = \left(1 - \frac{A_E}{A_C}\right)\sigma'_{radial}$$

Suction imposition technique:
s ≤ 50 kPa: water sub-pressure
s = 100 kPa: axis translation

Tests by the "triaxial traction method"



$$\sigma_3' = \sigma_t'$$



(compression)

$$q = 3\left(p' - \sigma_t'\right)$$

Main points:

1. At s = 0 kPa, remoulded Bioley silt cannot sustain significant tensile stress → cut-off

2. As suction increases, negative net stress can be experienced and brittle failure is promoted. At low stresses, tensile failure become apparent.

3. The criterion is shifted towards positive values of effective stress as suction increases.

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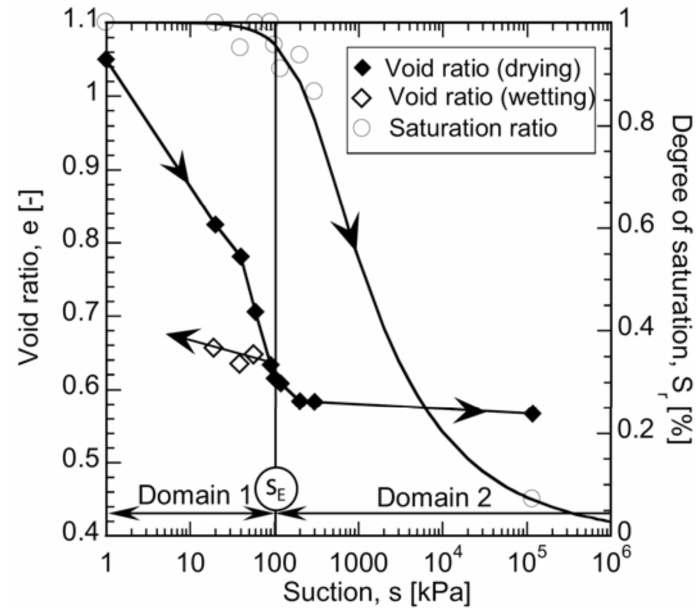
Constitutive modelling for soils subjected to desiccation

What we aim at modelling



Key point 1:
Domain 1: shrinkage mostly irrecoverable, follows NCL.
Domain 2: residual shrinkage, recoverable.
Elasto-plastic constitutive approach.

Key point 2:
Desiccation cracks in initially saturated remolded soil occur in Domain 1.

Key point 3:
Desiccation crack essentially mode I failure.
Crack must be described with a tensile failure criterion.

Key point 4: The tensile failure criterion should be expressed in effective stress.

Key point 5: The tensile failure criterion depends on suction.

Existing models: can fall in several categories
(i) Do not use effective stress and elasto-plasticity.
(ii) Model only Domain 1 (use of Terzaghi's effective stress) in simplified conditions.
None of them features a tensile failure criterion (points 3, 4 and 5).

Constitutive modelling

- Uses the **Bishop's generalized effective stress**:

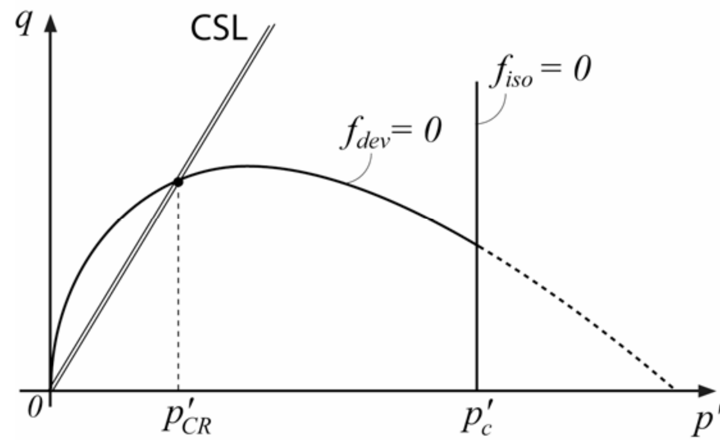
$$\boldsymbol{\sigma}' = \boldsymbol{\sigma} - p_g \mathbf{I} + S_r (p_g - p_l)\mathbf{I}$$

"Effective Stress Concept in Unsaturated Soils: Clarification and Validation of a Unified Framework". International Journal of Numerical and Analytical Methods in Geomechanics, 2008.

- Uses the **original Hujeux model**:
  Strain hardening elasto-plastic constitutive model, based on the critical state concept

- **Elastic part**

$$d\varepsilon_v^e = \frac{dp}{K(p')} \qquad d\varepsilon_d^e = \frac{dq}{3G(p')}$$



- **Two plastic mechanisms:** $d\varepsilon_{ij}^p = d\varepsilon^{p,iso}\delta_{ij} + d\varepsilon_{ij}^{p,dev}$

Isotropic $f_{iso} = p' - p'_c \; r_{iso}$

Deviatoric (non-associated) $f_{dev} = q - Mp'\left(1 - b \log \frac{p'}{p'_{CR}}\right) r_{dev} = 0$

Hardening law: $p'_c = p'_{c0} \exp\left(\beta \varepsilon_v^p\right)$

Remark: with the generalized effective stress concept, the CSL always meets the axis origin, whatever the suction is.

Constitutive modelling

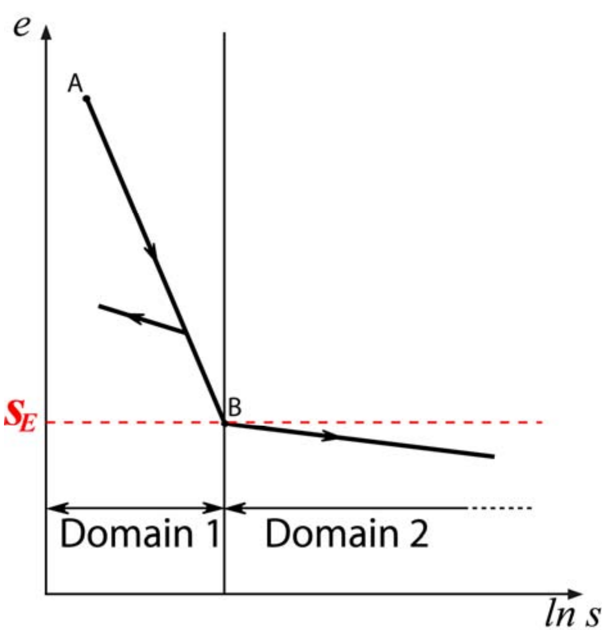
Extension to unsaturated case

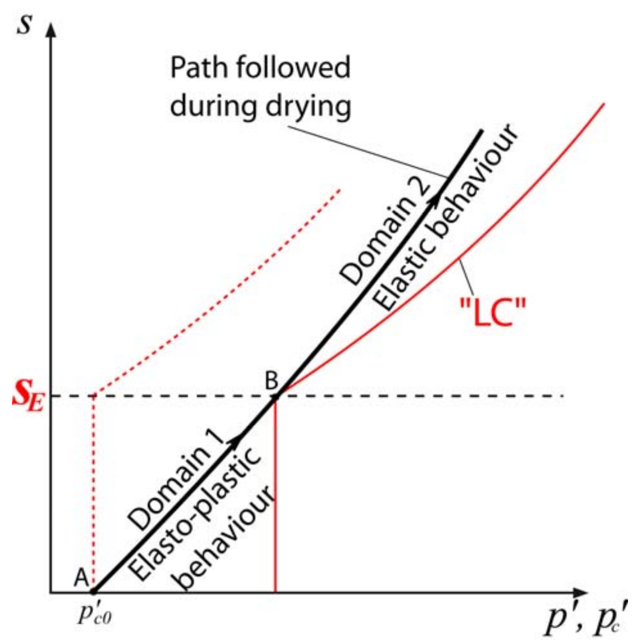
Above air entry value, there is an increase of preconsolidation pressure due to suction:

$$p'_c = p'_{c0} \exp\left(\beta \varepsilon_v^p\right) \qquad \text{if } s \leq s_E$$

$$p'_c = p'_{c0} \exp\left(\beta \varepsilon_v^p\right)\left[1+\gamma_s \log\left(\frac{s}{s_E}\right)\right] \qquad \text{if } s > s_E$$

This makes possible simulation of Domains 1 and 2.



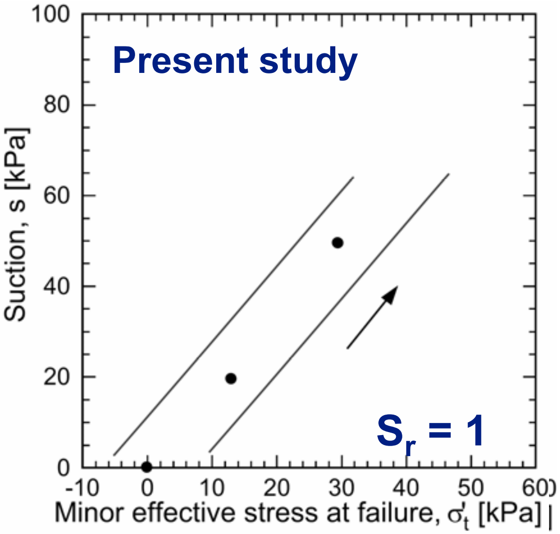


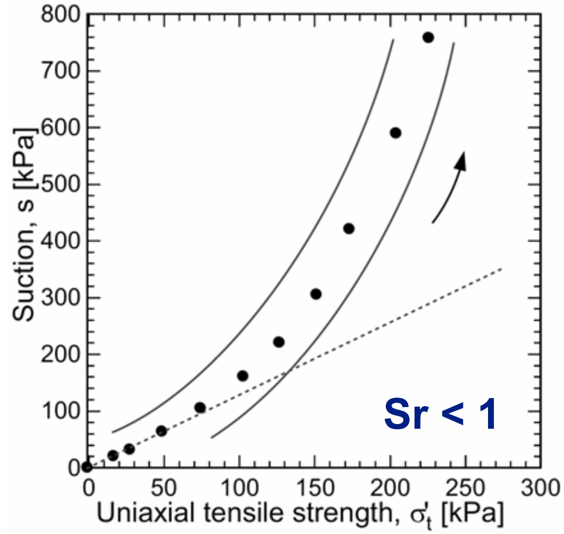
Changes of saturation ratio with suction are managed with van Genuchten relation:

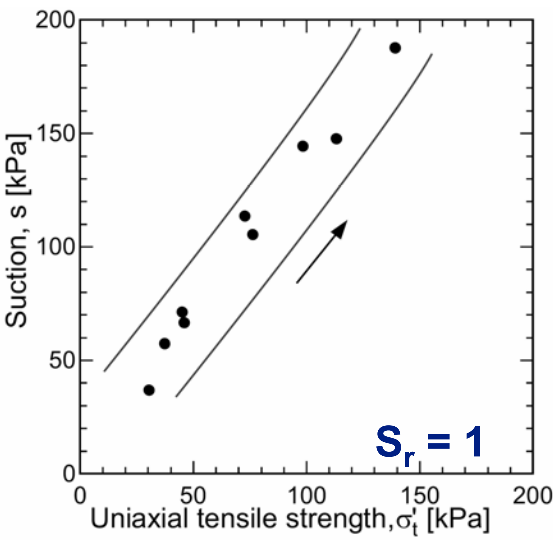
$$S_r = \left[\frac{1}{1+(\alpha_s s)^{n_s}}\right]^{m_s}$$

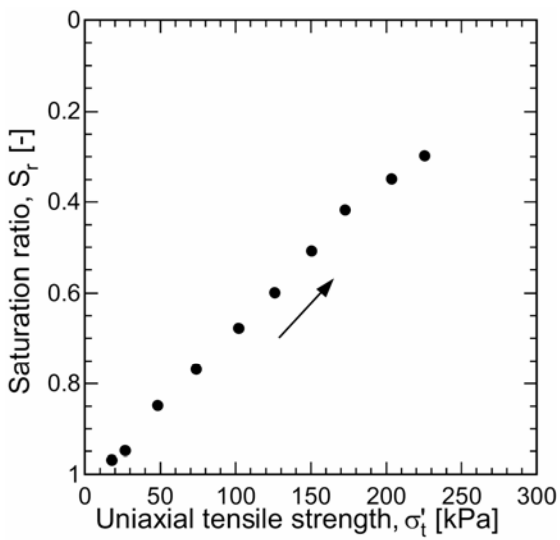
Proposition of a tensile failure criterion (1/2)

➢ **A tensile failure criterion is required to model desiccation cracks:**
5 batches of tensile tests of the literature + present study are used to determine it





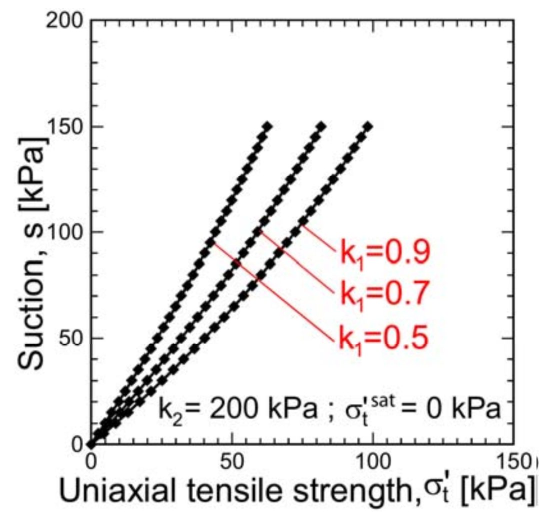




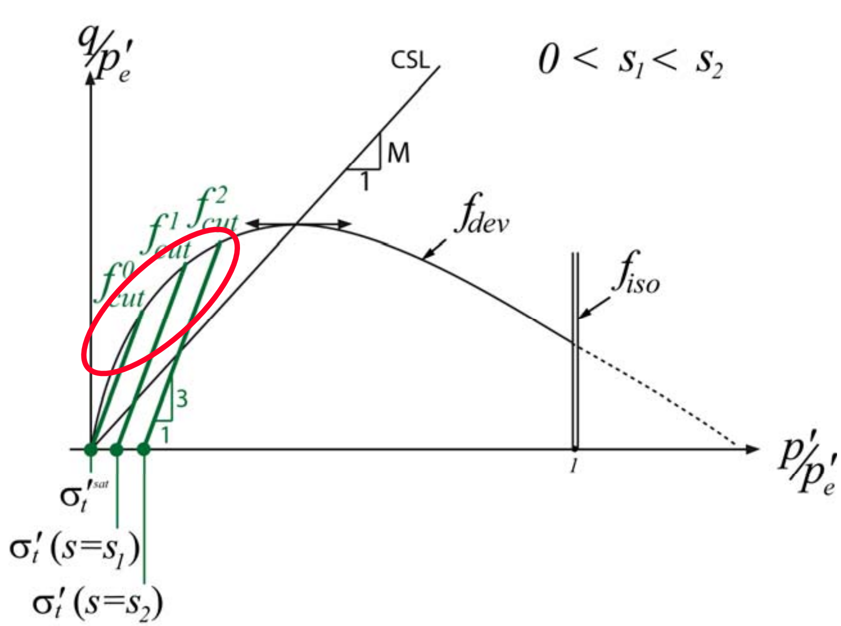
➢ **Proposition of a law for tensile strength evolution with suction:**

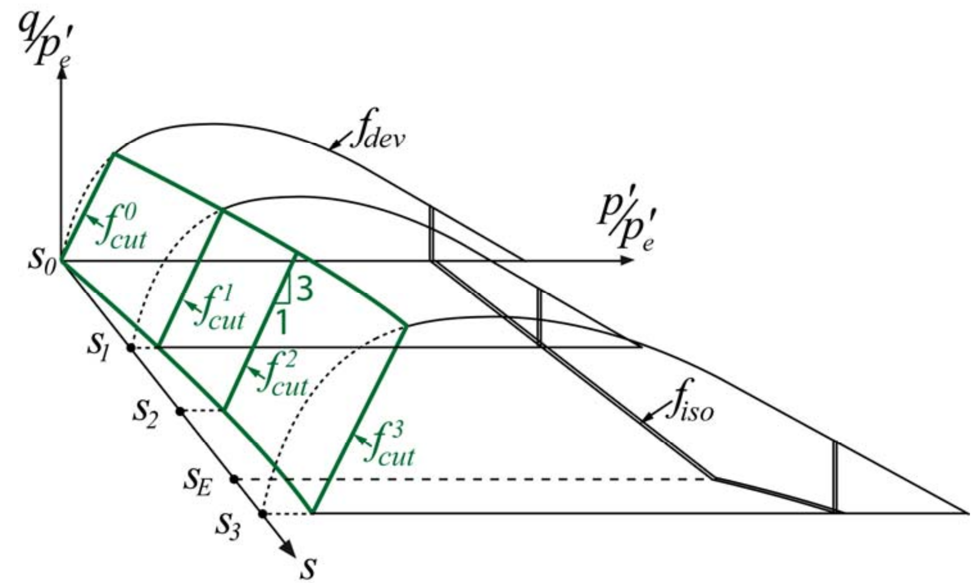
$$\sigma'_t = \sigma'^{sat}_t + k_2\left[1 - \exp\left(-\frac{k_1 s}{k_2}\right)\right]$$

➢ **Significance of the parameters:**



Proposition of a tensile failure criterion (2/2)



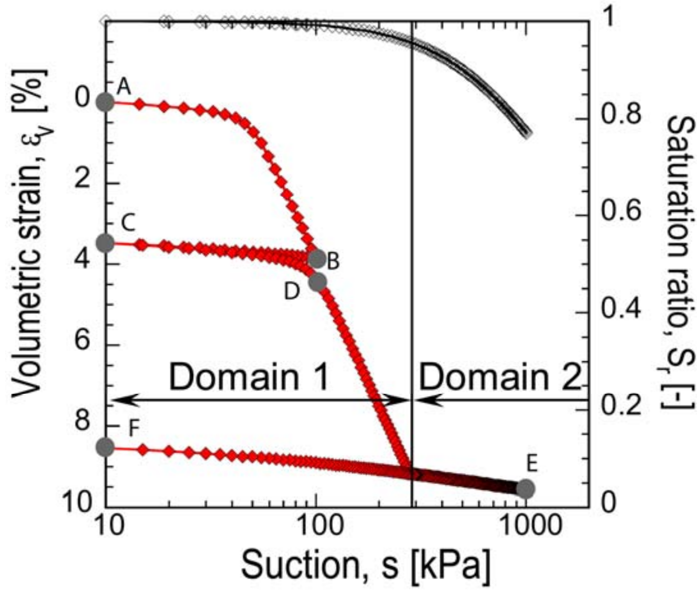


- The following criterion is adopted: $\sigma'_3 = \sigma'_t$ → Griffith criterion
- For compression state, it defines a line of slope 3 in the q-p' plane.
- The form of the criterion in the circled zone is only inferred.

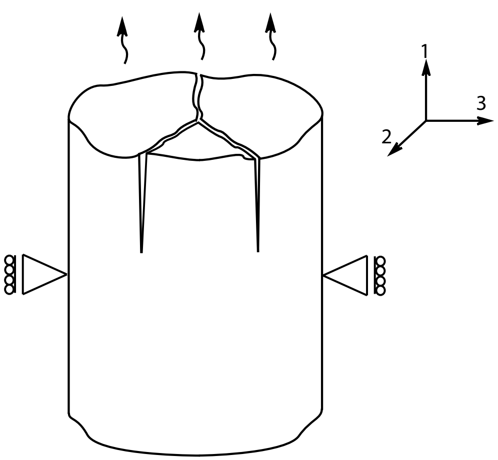
Model typical features

- **Free desiccation**

Activation of the isotropic mechanism through an increase of mean effective stress

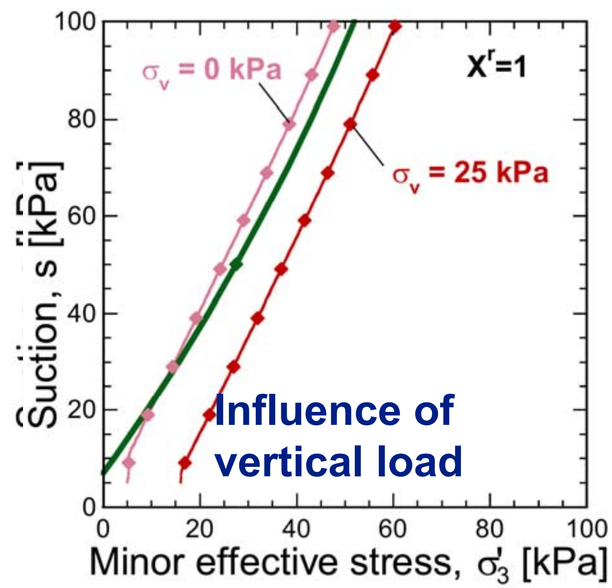


- **Constrained desiccation: case of a soil column with lateral strain restriction**



One can manage constrained desiccation with a "degree of shrinkage restraint" X^r

$$d\varepsilon_3\big|_{imp} = \left(1 - X_3^r\right) d\varepsilon_3^s$$



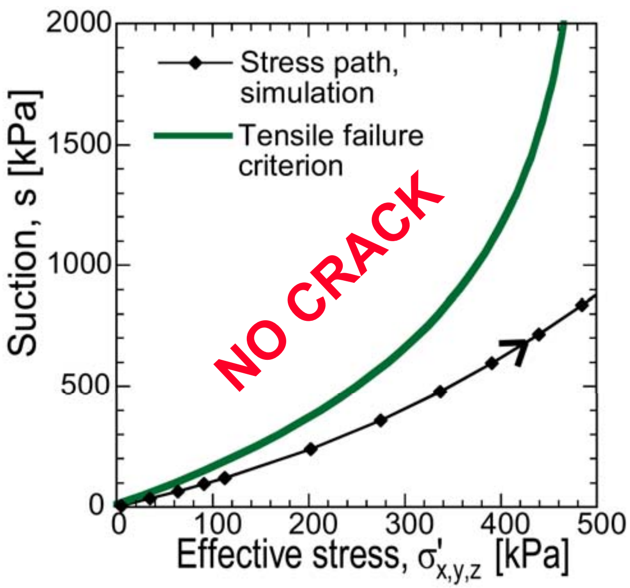
Validation (1/3)

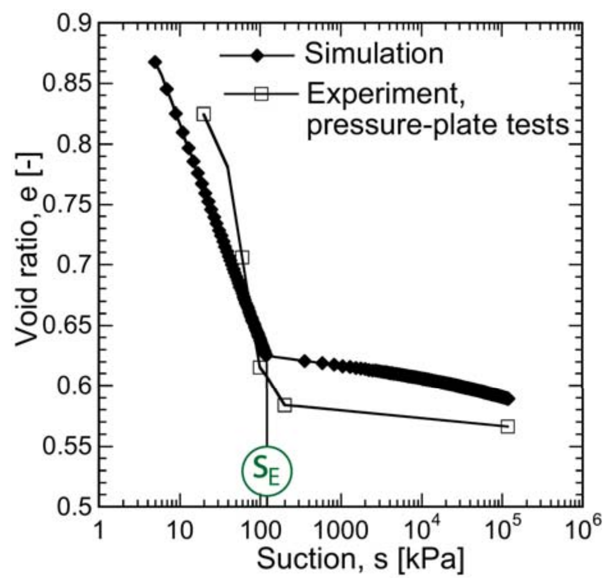
Desiccation tests (present study)

➢ **Parameters determined with our consolidation, CTC, WRC, and traction tests on Bioley silt:**

Elastic	K_{ref} [MPa] / G_{ref} [MPa] / n [-]	**212.2 / 98 / 0.69**
Plastic	β^{sat} [-] / ϕ'_C [°] / ϕ'_E [°] / d[-] / p'_{CR0} [kPa]	**24.5 / 31.5 / 25 / 2 / 5**
Tensile failure	$\sigma_t'^{sat}$ [kPa] / k_1 [-] / k_2 [kPa]	**-6 / 0.72 / 5x10^2**
Unsat. mechanical and water retention behaviour	s_E [kPa] / γ_s [-]	**120 / 7**
	α_s [-] / n_s [-] / m_s [-]	**4x10^{-6} / 1.8 / 0.24**

Simulation of pressure plate tests (and free desiccation tests) :

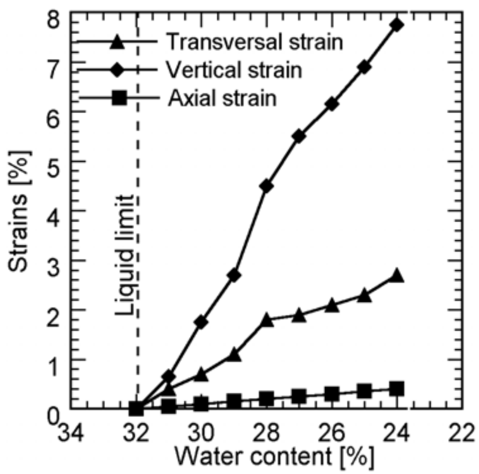


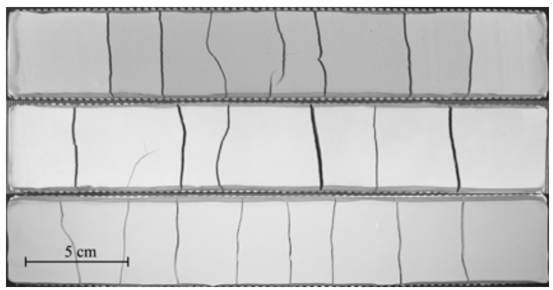


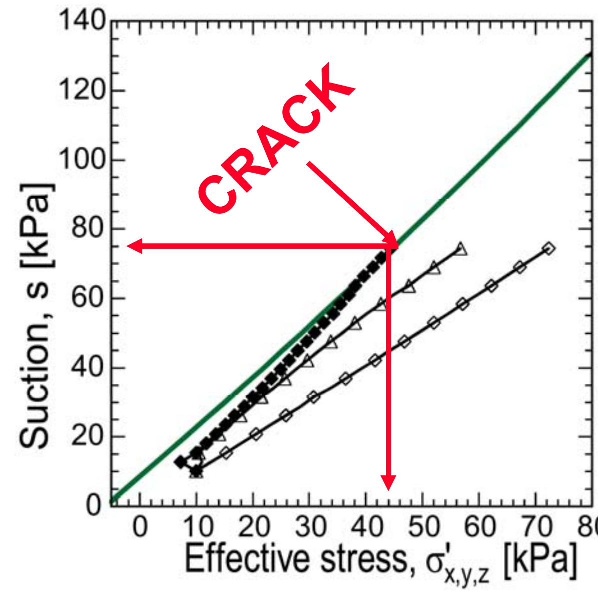
Validation (2/3)

Desiccation tests (present study)

Constrained desiccation: the loading of the simulation is the measured strain field (vertical / axial / transversal) during the constrained desiccation tests.







The suction at which the first crack appears is fairly predicted (corresponds to the measured value).

The corresponding saturation ratio is almost equal to 100%.

Validation (3/3)

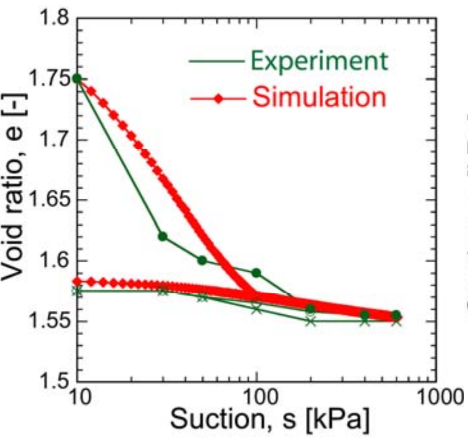
Tests of Rodriguez et al. (2007)

➢ **Soil: mining waste (ML low plasticity silt)**

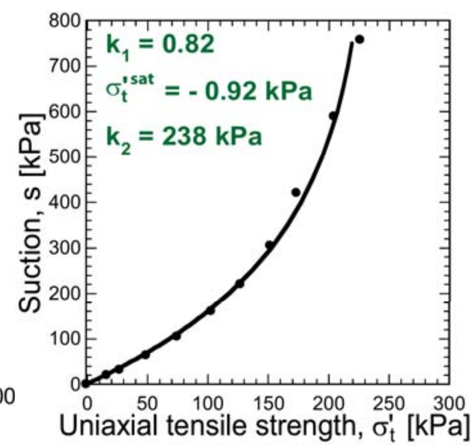
➢ **Tests performed:**
WRC in K0 conditions,
Uniaxial traction test at various suctions
Air drying of thin slabs on grooved surface

➢ **Back predictions:**

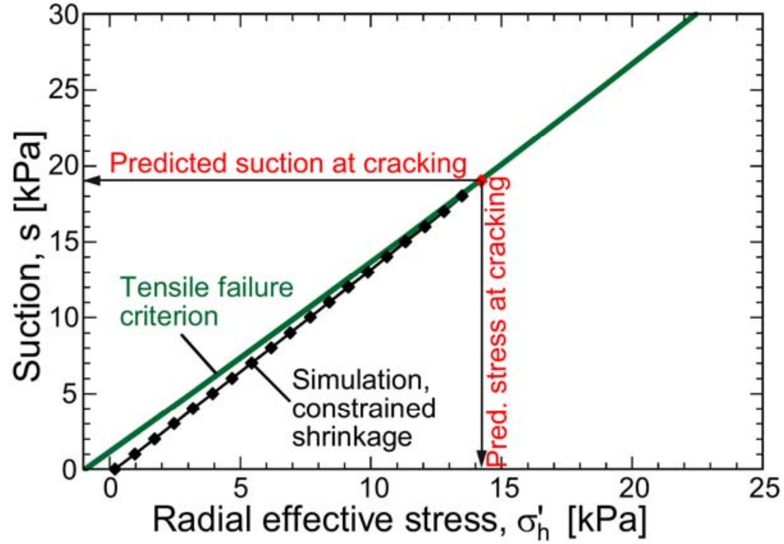
WRC



Tensile tests



➢ **Simulation of constrained desiccation:**



Good correspondance with exp. cracking suction.

Conclusions (1/2)

1. Mechanisms of desiccation crack initiation:

- Existence of two domains of drying shrinkage with distinct behaviours.
- Cracking of initially remoulded saturated soil occurs when Sr is still close to unity.
- Tensile strength (expressed with effective stress) increases with suction and is shifted towards positive values.
- There must be a relationship between the tensile strength, the fluid pressures and the degree of saturation. In the test conditions, such variables are critical close to air entry value.
- Crack pattern geometry (such as crack spacing and interception) is the result of energy redistribution.

Conclusions (2/2)

2. Constitutive modelling:

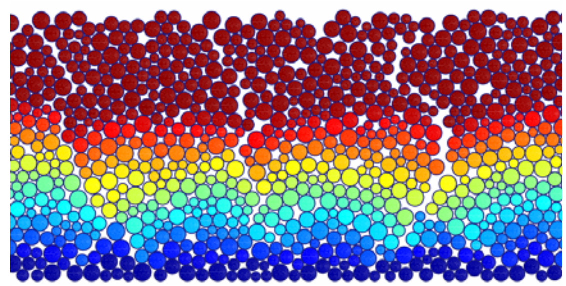
➢ A tensile failure criterion depending on the suction level has been developed and validated.

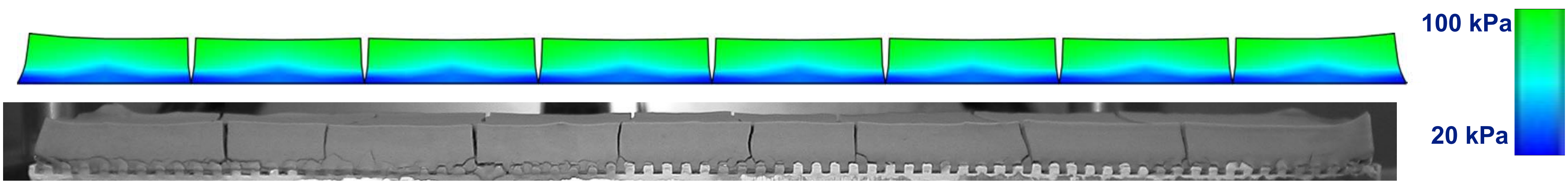
➢ The Originality and strength of the model: to combine advanced concept of effective stress and constitutive approach for unsaturated soils with tensile failure.

➢ Shrinkage / suction / stress / strength and cracking are included in a unified framework.

3. Desiccation crack propagation:

In progress – XFEM and DEM

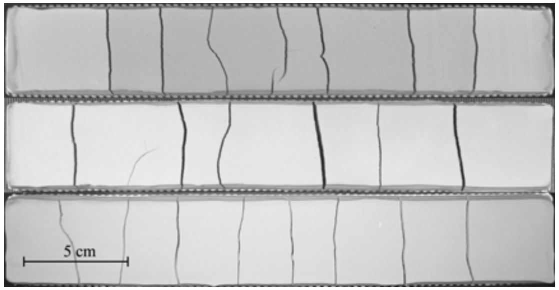




Thank you

for your attention

Constrained desiccation test results (4/4)



Crack pattern formation

➢ **How to explain it?**

➢ **First possibility: "global" considerations at the scale of the entire bar, considering a homogeneous stress field.**

Energy *U* stored during constrained deformation:

$$U = \frac{ELhl\left(\varepsilon_x^m\right)^2}{2}$$

Energy W_s required to form the pattern of *N* crack:

$$W_s = N_c a_{cf} l G_c$$

Conservation of energy: equalling both terms:

$$N_C = \left(\frac{E}{G_c}\right)\frac{L\left(\varepsilon_x^h\right)^2}{2}$$

➢ **Second possibility:**

Stress analysis: the first crack split the bar in two new bars, this process is resumed to create higher order crack, until total stress release.