Swiss concept for HLW disposal (Nagra)

Geomechanics

LECTURE 11

GEOMECHANICAL BEHAVIOUR OF UNSATURATED GEOMATERIALS

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Laboratory of soil mechanics – Fall 2024

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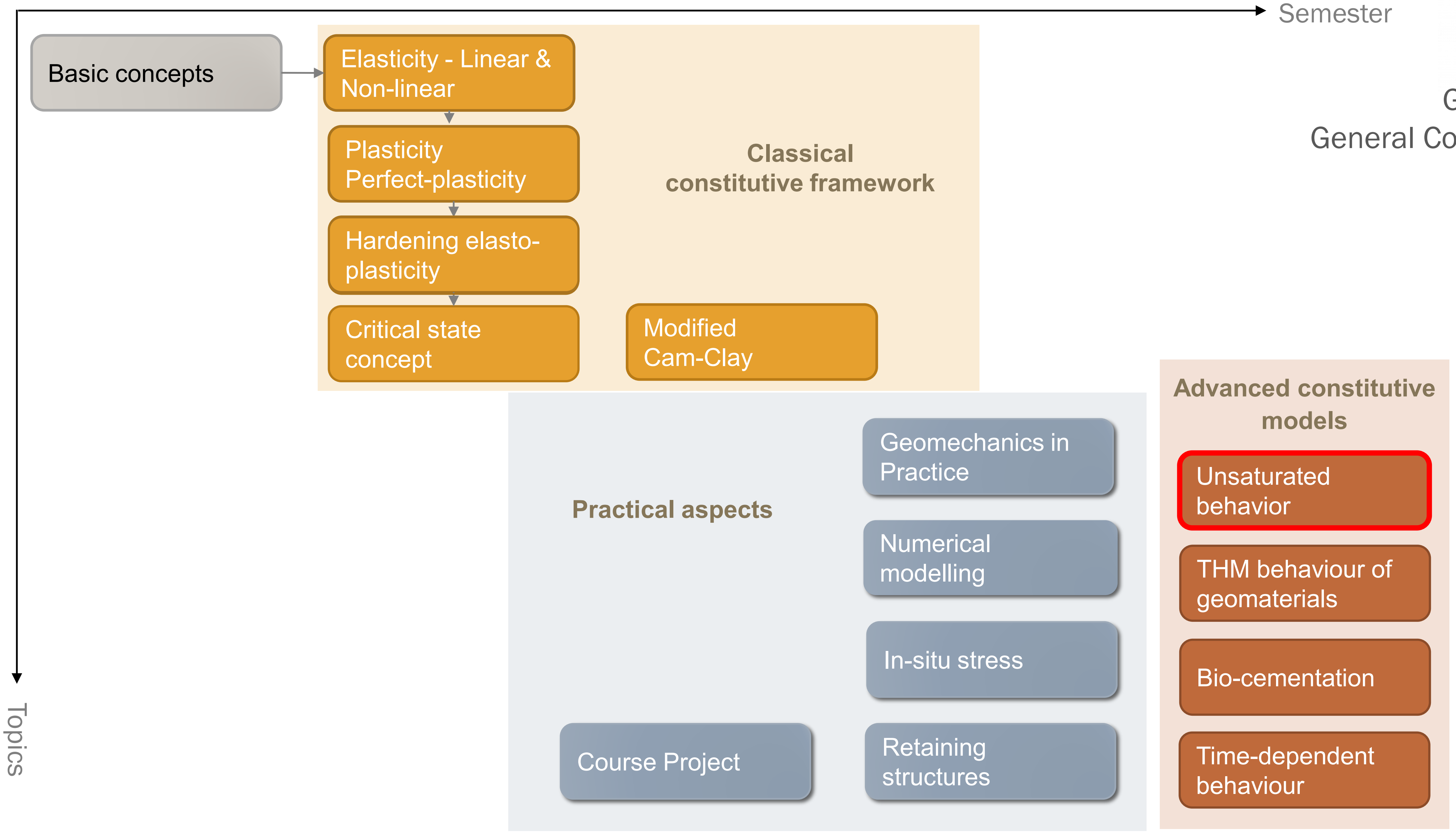
Access the QUIZ

https://etc.ch/A7r8

Geomechanics
General Course overview



Semester

Topics

Basic concepts

Classical constitutive framework

- Elasticity - Linear & Non-linear
- Plasticity Perfect-plasticity
- Hardening elasto-plasticity
- Critical state concept
- Modified Cam-Clay

Practical aspects

- Geomechanics in Practice
- Numerical modelling
- In-situ stress
- Retaining structures
- Course Project

Advanced constitutive models

- Unsaturated behavior
- THM behaviour of geomaterials
- Bio-cementation
- Time-dependent behaviour

Content

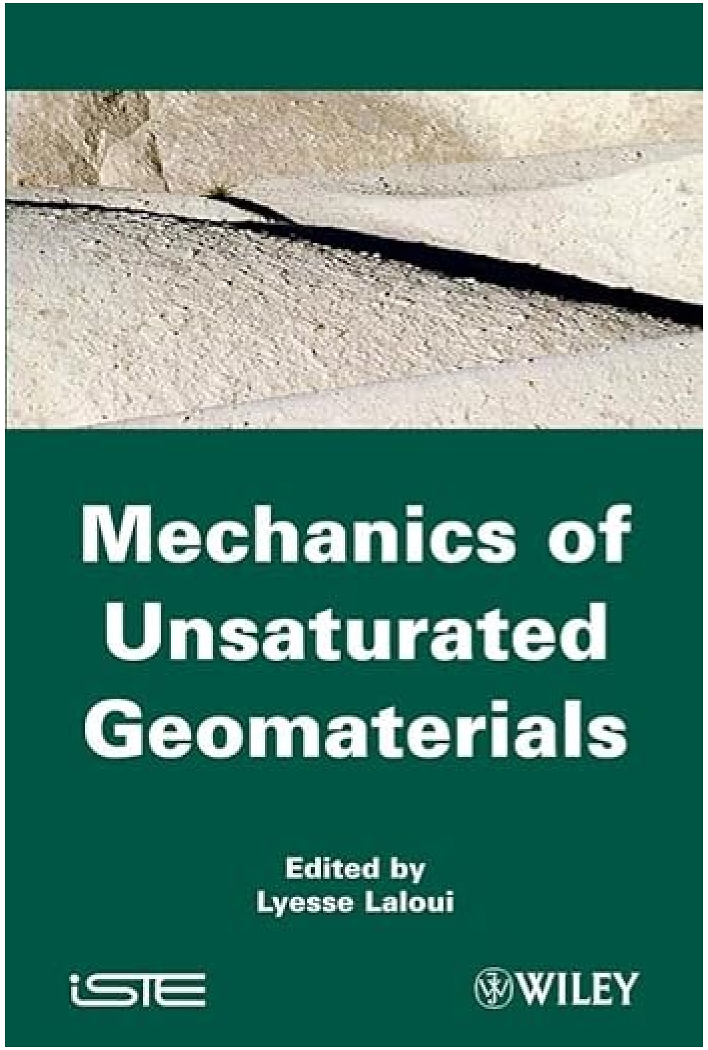
- Basic concepts
- Hydraulic properties of geomaterials under unsaturated conditions
- Mechanical behaviour of unsaturated geomaterials
- Conclusion

Basic concepts

INTRODUCTION

THE DEFINITION OF SUCTION

Useful reference



Mechanics of Unsaturated Geomaterials

Edited by
Lyesse Laloui

ISTE

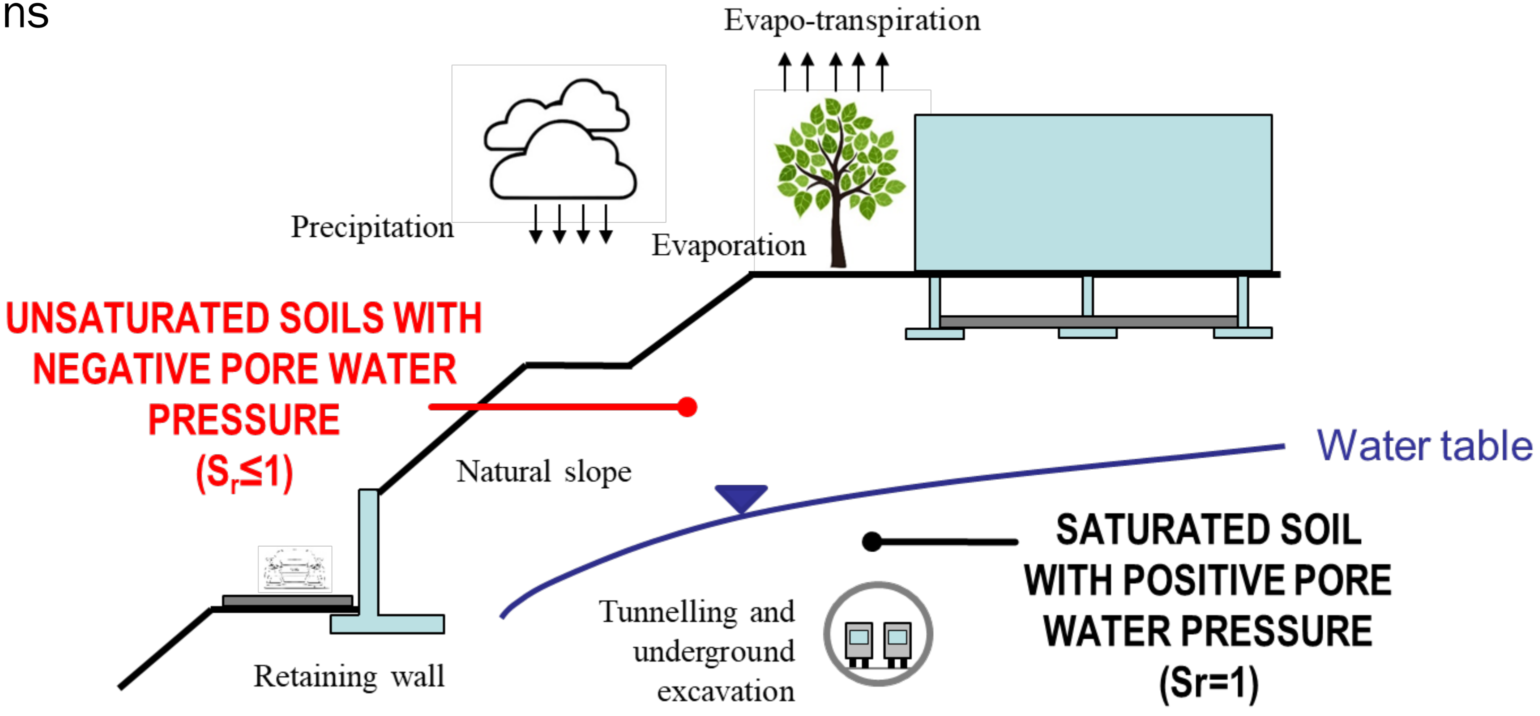
WILEY

Basic concepts unsaturated soils

Saturated and unsaturated states in practice

- Embankments and tunnels
- Road foundations
- At ground surface (infiltration and evaporation)
- Geoenvironmental engineering applications (nuclear and domestic waste storage)

Hydro-mechanical properties of the soil need to be characterized in saturated and in unsaturated conditions



Above the water table the pore water pressure is negative, and the soil can become unsaturated

Basic concepts unsaturated soils

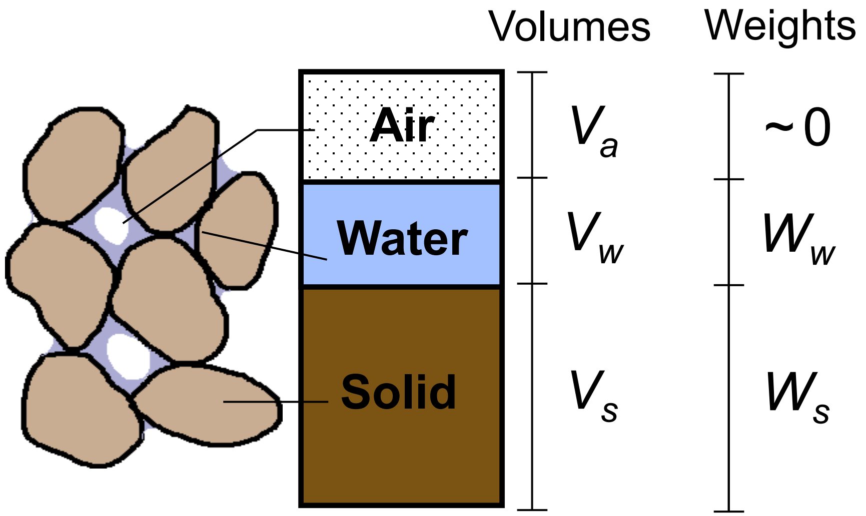
Unsaturated soils

3 phases

- Gas phase (air)
- Liquid phase (water)
- Solid phase (solid particles)

3 stress variables

- σ total mechanical stress
- p_w porewater pressure
- p_a pore-air pressure



Three-phase description

Many ways to quantify the amount of water

- Gravimetric water content $w = W_w/W_s$
- Degree of saturation $S_r = V_w/Vv$
- Volumetric water content $q = V_w/V$
- Water ratio $e_w = V_w/Vs$

- Volume of voids $V_v = V_a + V_w$
- Total volume $V = Vv + Vs$
- Porosity $n = Vv/V$
- Void ratio $e = Vv/Vs$

Basic concepts unsaturated soils

Complex interaction between water, air and solid phases

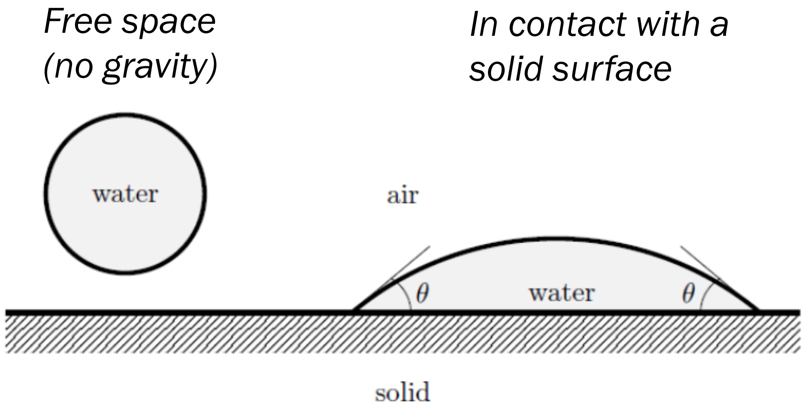
Surface tension, T:

- energy per unit area of the surface between phases
- energy penalty of breaking the intermolecular interactions between the two phases, and instead creating an interface between them

Contact angle, θ:

- angle between two fluids on a solid surface
- expresses the wettability of the solid
- measured through the denser phase, usually water

Fluid arrangements

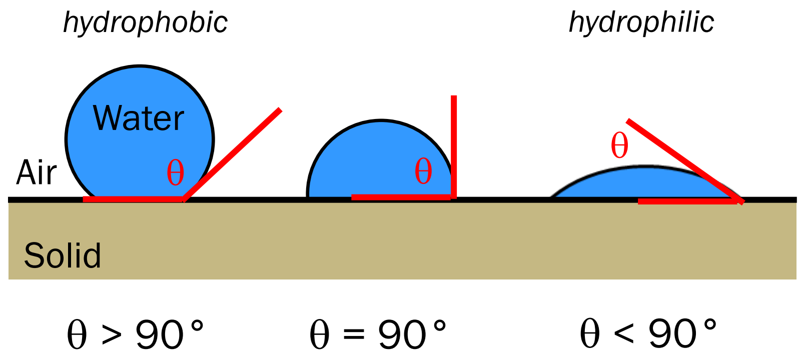


Representative values

Air/water: 72 mN/m

Oil/water: 50 mN/m

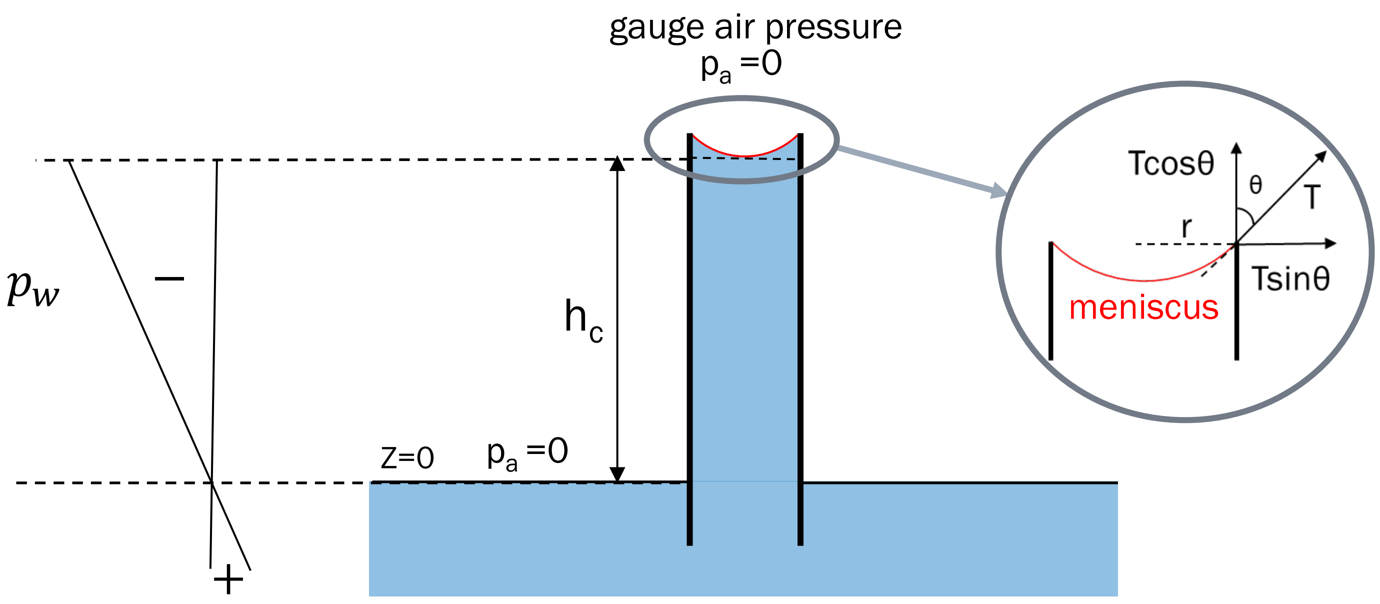
Air/oil: 20 mN/m



Basic concepts unsaturated soils

Complex interaction between water, air and solid phases

- The interface air-water near a solid surface has a curvature due to **surface tension**
- The water in the voids is similar to the water in a capillary tube.



T: Surface tension (force per unit of length)
θ: contact angle (it depends on the characteristics of the liquid and the solid)

Vertical equilibrium of the water column

$$\gamma_w h_c \pi r^2 = 2\pi r T cos\theta$$

$$h_c = \frac{2\pi r T cos\theta}{\gamma_w \pi r^2} = \frac{2T cos\theta}{\gamma_w r}$$

$$p_w = -\gamma_w h_c = -\frac{2T cos\theta}{r}$$

The gauge water pressure is negative (p_w)

Young-Laplace equation

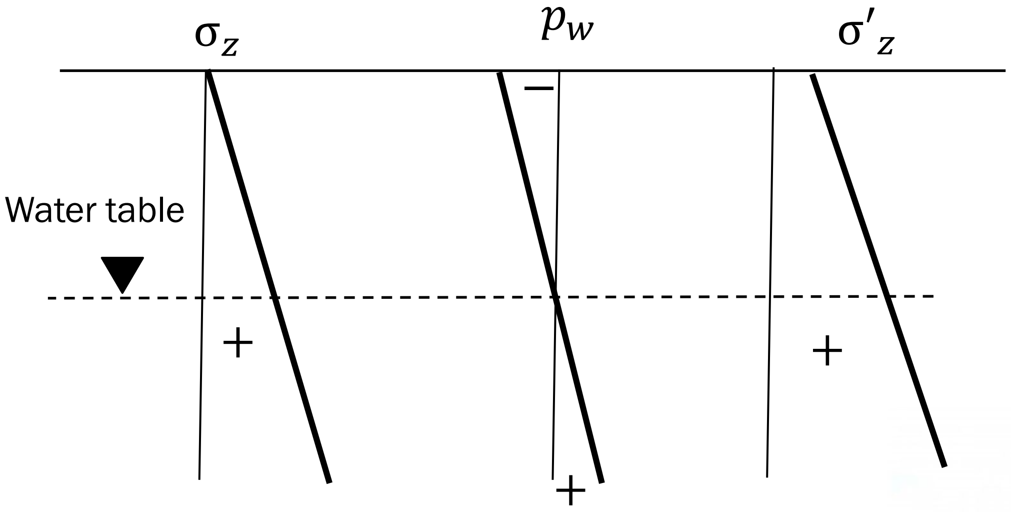
$$\boxed{s = p_a - p_w = \frac{4T cos\theta}{D}}$$

Suction s

$$D = 2r$$

Basic concepts unsaturated soils

A **negative pore water pressure** allows having **non-zero effective stresses** even at a zero depth.



The <u>sand castle</u> is an example of how the negative pore water pressure in nearly saturated states affect the mechanical properties of soils.

The **Terzaghi's effective stress** can be considered still valid if the soil remains saturated even with negative pore water pressure

$$\sigma'_z = \sigma_z - p_w$$

⬇

The **shear strength** can be higher than zero even for a granular non-cemented soil at zero depth

$$\tau_f = c' + \sigma'_n tan\varphi'$$

Basic concepts unsaturated soils

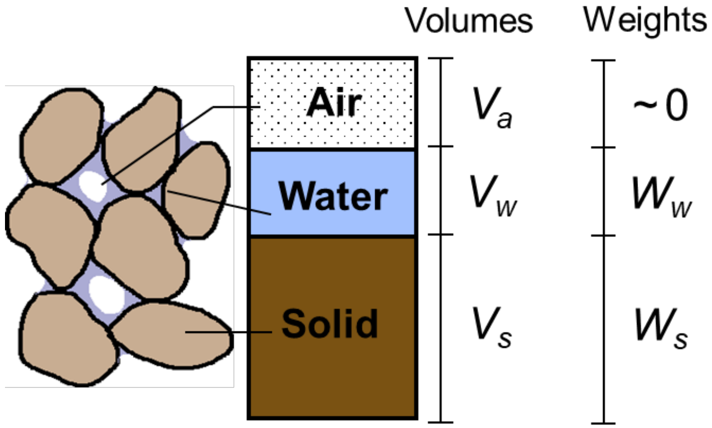
Unsaturated soils

3 phases

- Gas phase (air)
- Liquid phase (water)
- Solid phase (solid particles)

3 stress variables

- σ total mechanical stress
- p_w porewater pressure
- p_a pore-air pressure



Three-phase description

A complete description of the rheological behaviour of unsaturated soils requires

- Soil water retention behaviour *How Sr changes for a given suction ?*
- Stress-strain behaviour *How the soil deforms?*

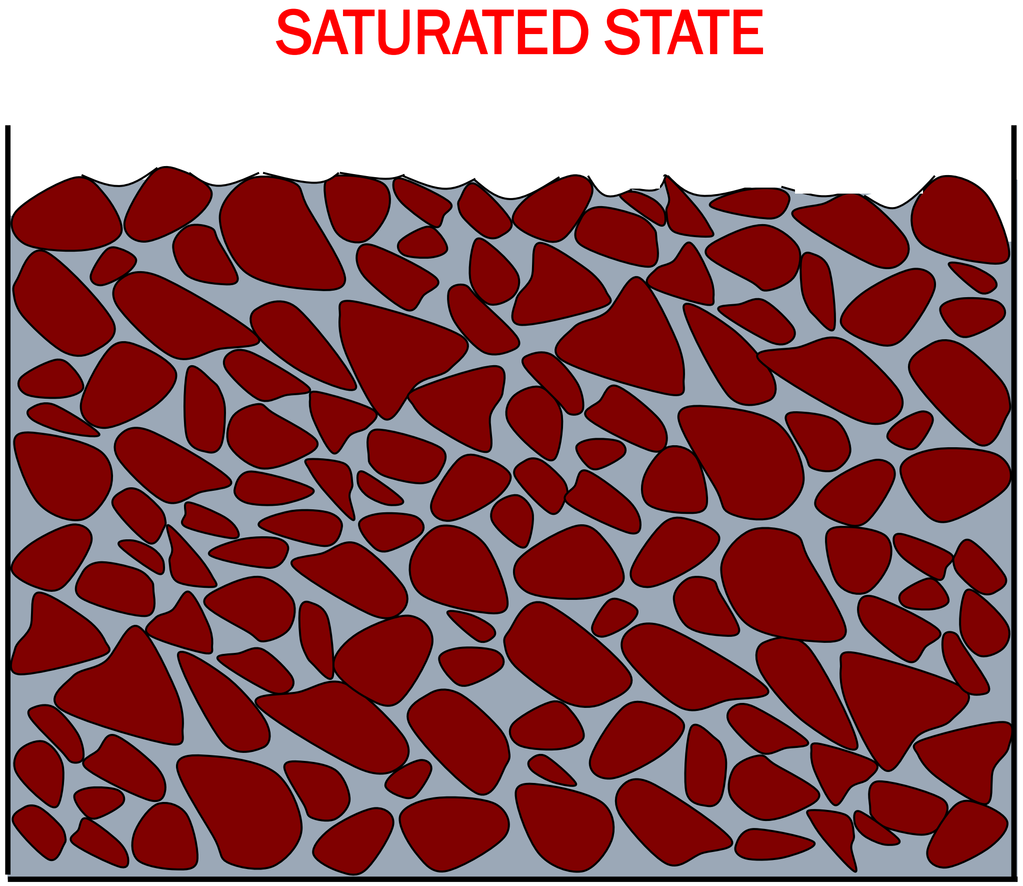
	Stress variables	Work-conjugate variables
Stress-strain variables for constitutive modelling of unsaturated soils	$\begin{pmatrix} \sigma' \\ s \end{pmatrix}$	$\begin{pmatrix} \varepsilon \\ Sr \end{pmatrix}$

Hydraulic properties of geomaterials under unsaturated conditions

THE WATER RETENTION CURVE

THE PERMEABILITY

The water retention curve

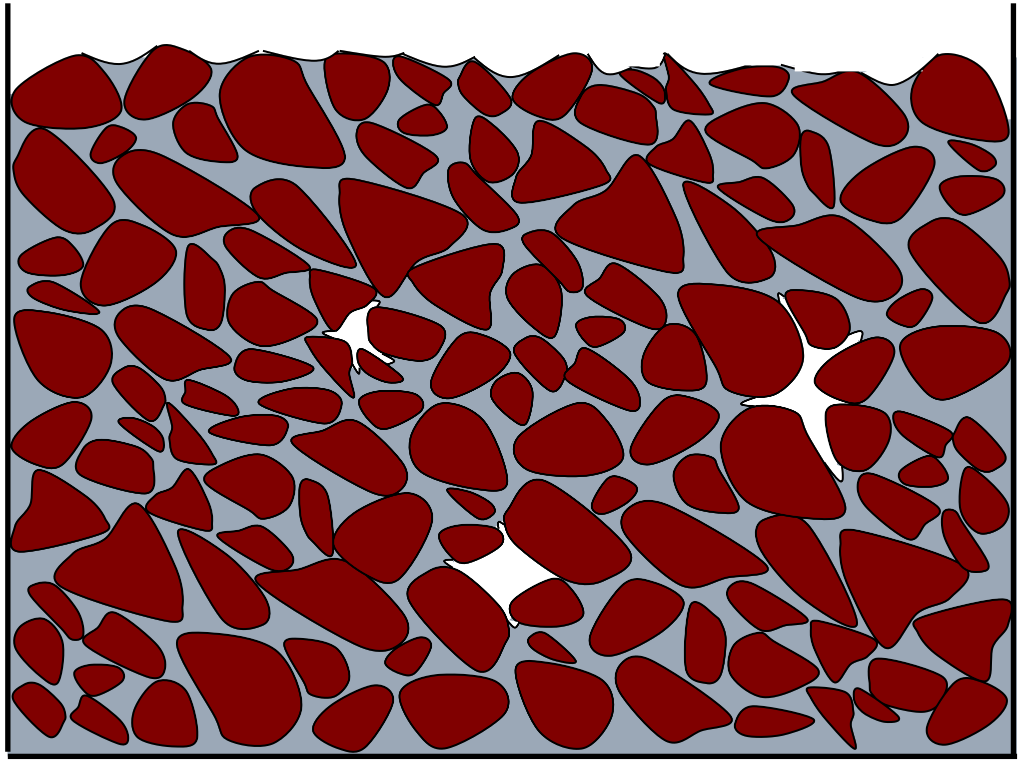


An initially saturated geomaterial is subjected to evaporation

- **Menisci** at the surface start to appear
- The pore water pressure decreases and the suction becomes higher than 0, **$s > 0$**
- The soil is still saturated, **$S_r = 1$**

The water retention curve

QUASI - SATURATED STATE

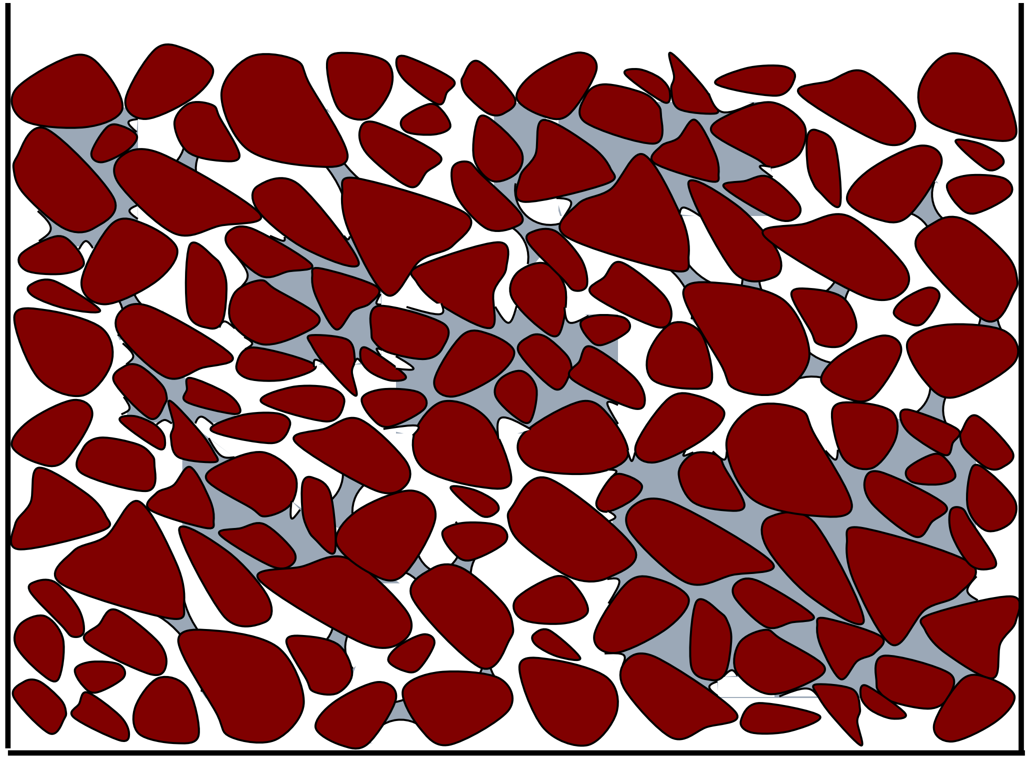


Indicative values of the degree of saturation
0.85-0.90 < Sr < 1

- The pore water pressure continues decreasing and the suction continue increasing, **s>0**
- More menisci appear, air cavities in the larger pores expand due to negative porewater pressure
- **Gas** phase is **discontinuous**, **liquid** phase is **continuous**
- The degree of saturation decreases, **S_r<1**

The water retention curve

PARTIALLY SATURATED STATE



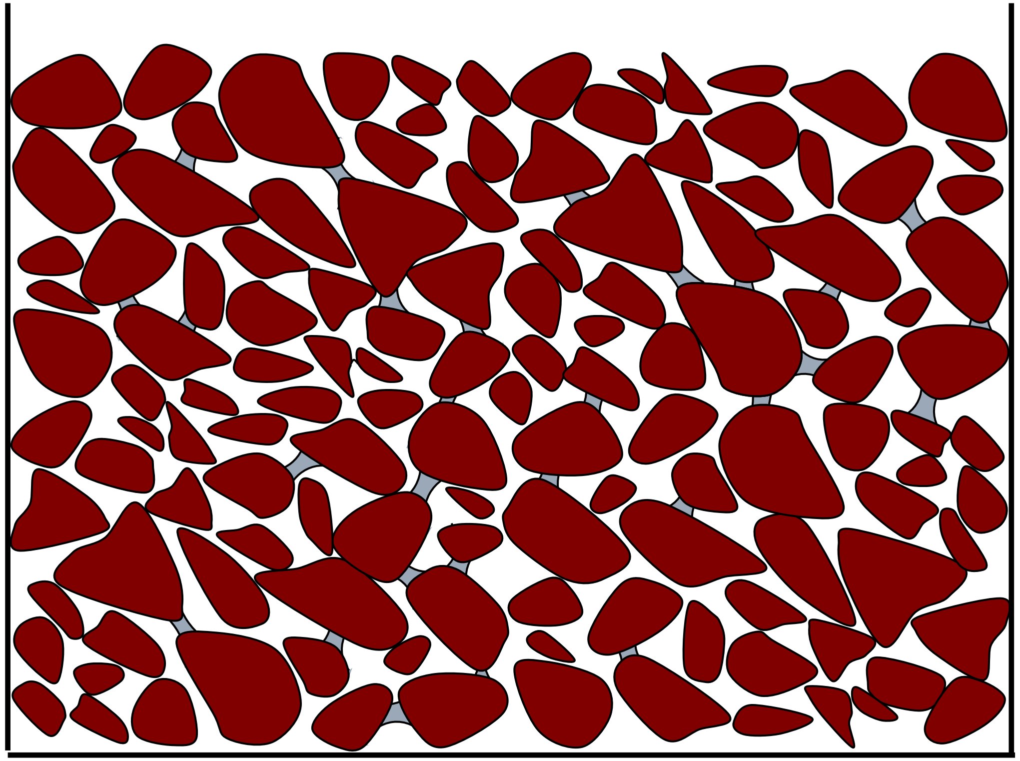
Indicative values of the degree of saturation

$0.1 < S_r < 0.85\text{-}0.90$

- More menisci appear, smaller pores start to desaturate;
- At the interface, the maximum curvature of the menisci is reached, and the air enter
- The pore water pressure continues decreasing and the suction continues increasing, **$s>0$**
- **Gas** phase is **continuous**, **liquid** phase is **continuous**
- The degree of saturation decreases, **$S_r<1$**

The water retention curve

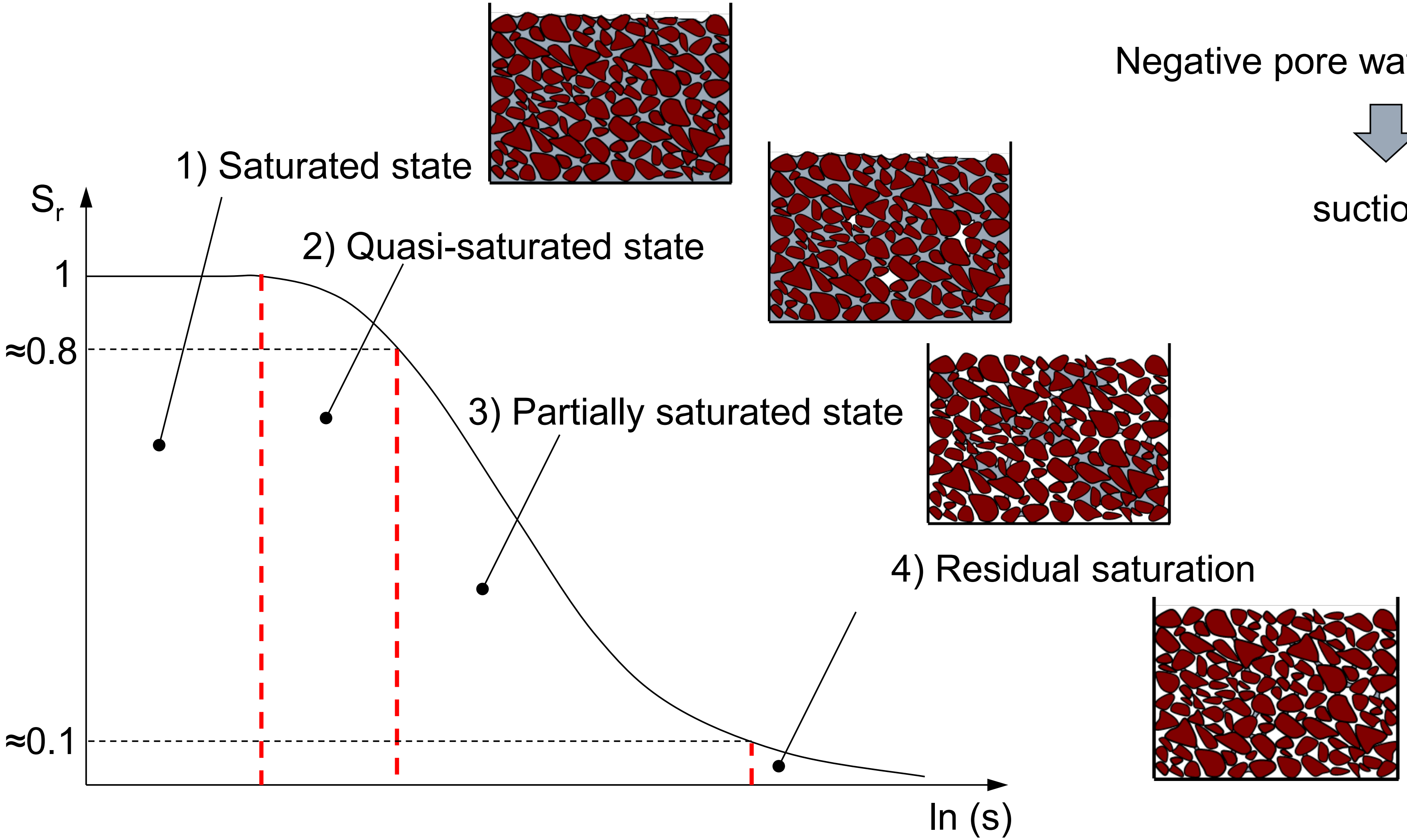
RESIDUAL STATE



Indicative values of the degree of saturation
$S_r < 0.1$

- There is water in some isolated pores
- The pore water pressure continues decreasing and the suction continues increasing, **s>0**
- **Gas** phase is **continuous**, **liquid** phase is **discontinuous**
- The degree of saturation does not decrease significantly

The water retention curve



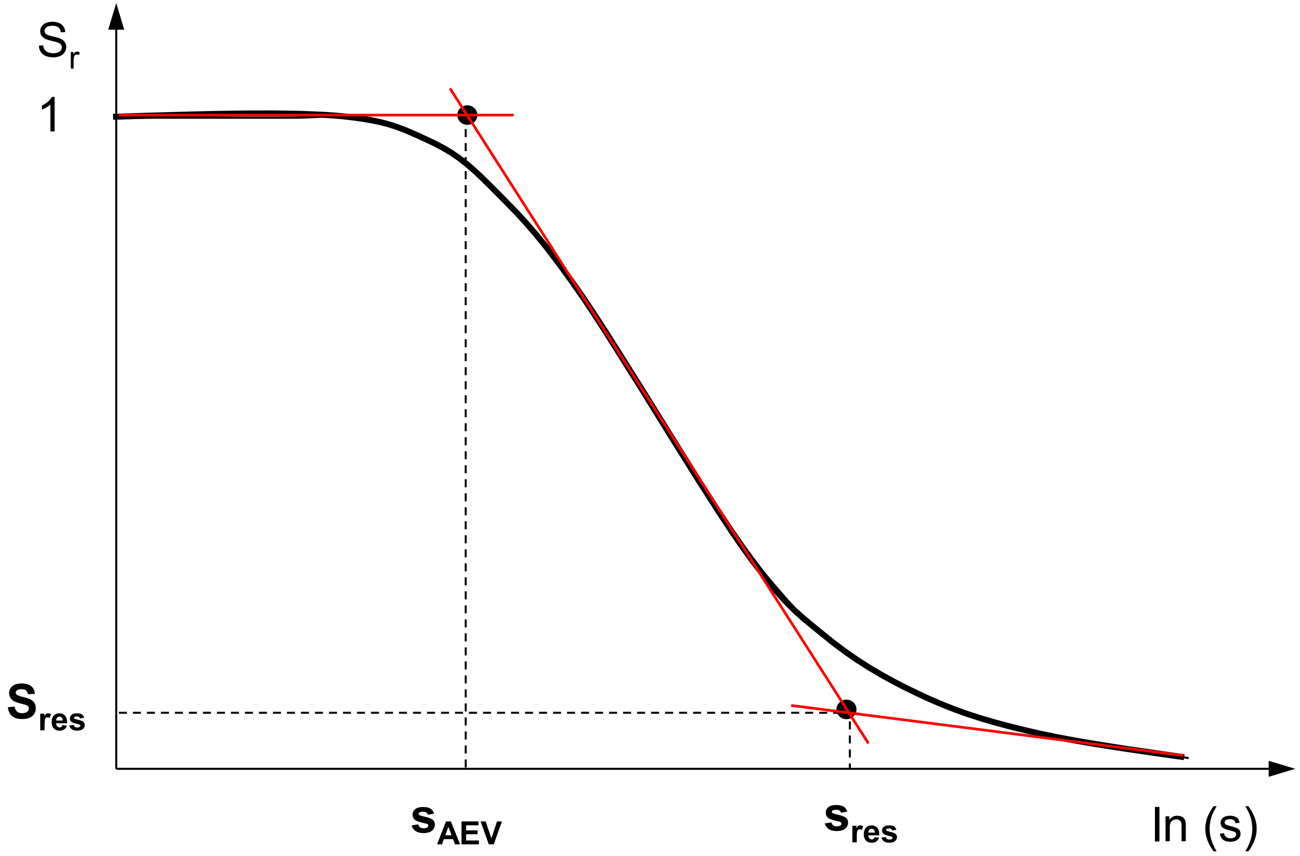
Negative pore water pressure **(p_w)**

⇩

suction **(s)**

The water retention curve

The relationship between the degree of saturation and the suction is called “**water retention curve**”. It expresses the capacity of the soil to retain water



Key parameters

s_{AEV} = air entry value

s_{res} = residual suction

S_{res} = residual degree of saturation

The water retention curve

THE AIR ENTRY VALUE

- Value of suction from which the **soil start to desaturate**
- **Function of the pores size:** a lower suction is needed to desaturate a soil with larger pores

Young-Laplace equation

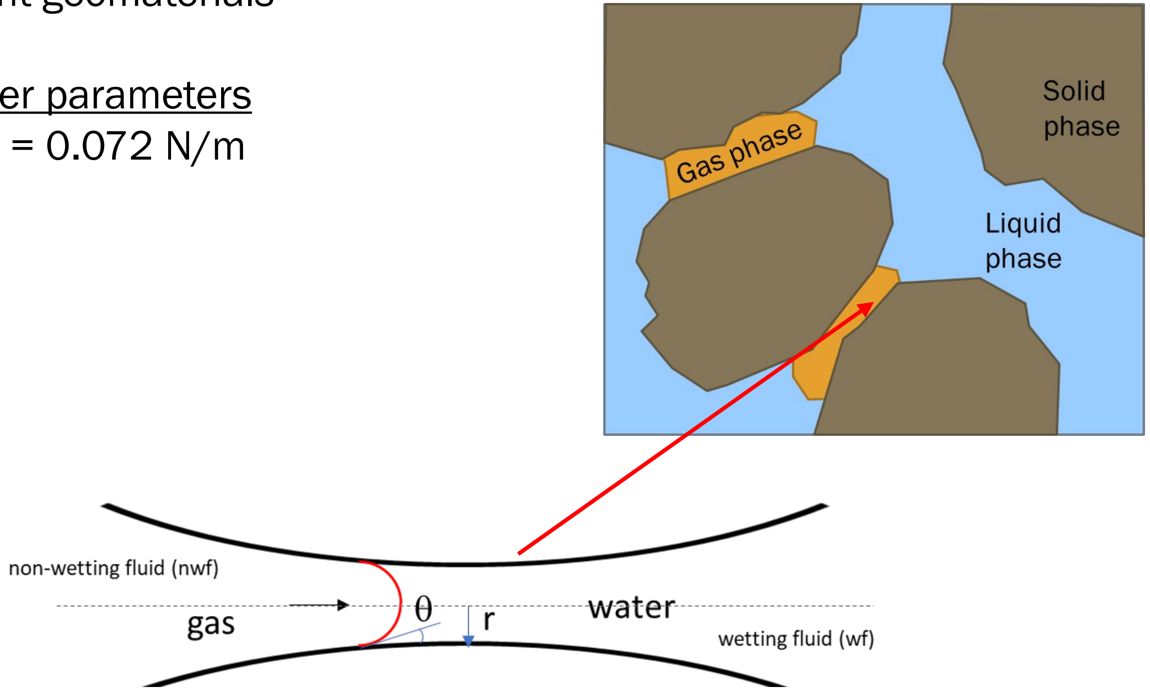
$$s = p_a - p_w = \frac{4T\cos\theta}{D}$$

D: pore diameter for different geomaterials

Values assumed for the other parameters
Water-air surface tension, T = 0.072 N/m
Water contact angle, θ = 0°

Order of magnitude of the air entry value depending on the characteristic pore size:

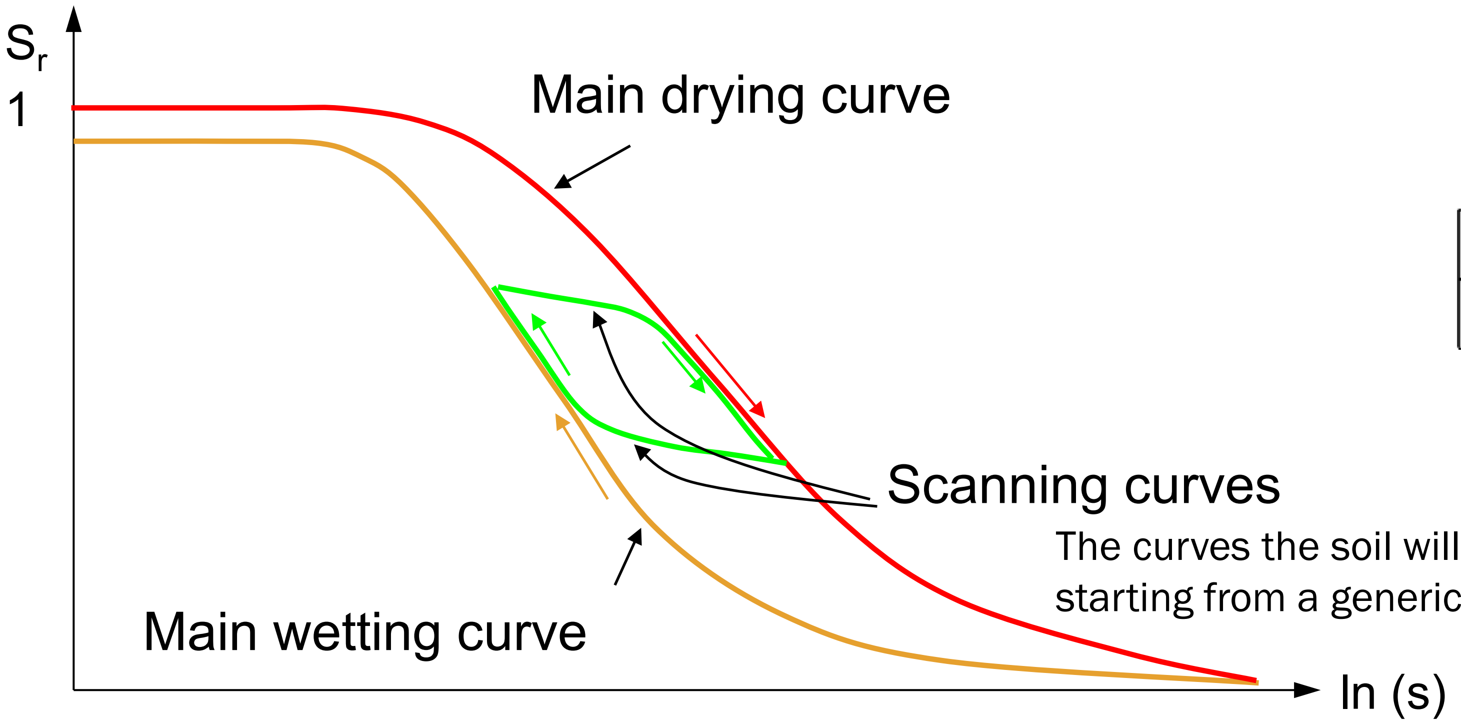
sand (d_{max}=30 μm)	silt (d_{max}=3 μm)	clay (d_{max}=0.3 μm)
9.6 kPa	96 kPa	960 kPa



The water retention curve

DRYING AND WETTING PROCESSES – HYSTERETIC BEHAVIOR

- Increase in suction is called “drying process”
- Decrease in suction is called “wetting process”
- The s-S_r relationship depends on the alternation of these processes

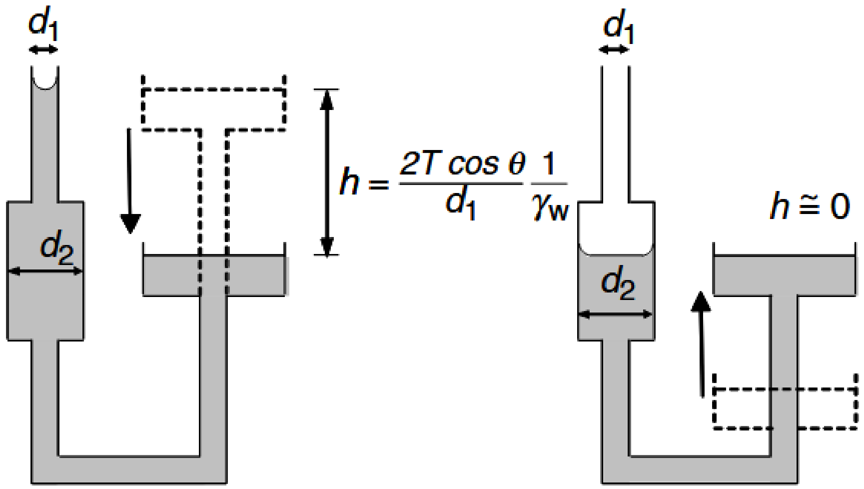


Main drying curve

Scanning curves

The curves the soil will follow starting from a generic state

Main wetting curve



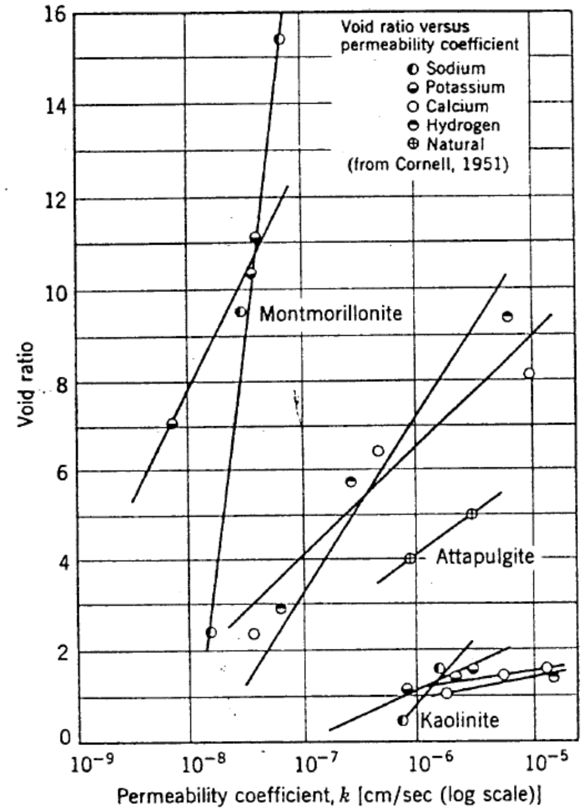
Laloui (2013)

The permeability

The **coefficient of permeability** is the coefficient of proportionality between the flow rate and the hydraulic head gradient. **Darcy's law** (for the x-direction) gives:

$$v_{w,x} = -k_w \frac{\partial h_w}{\partial x}$$

For a given **saturated soil**, the coefficient of permeability mainly depends on the void ratio

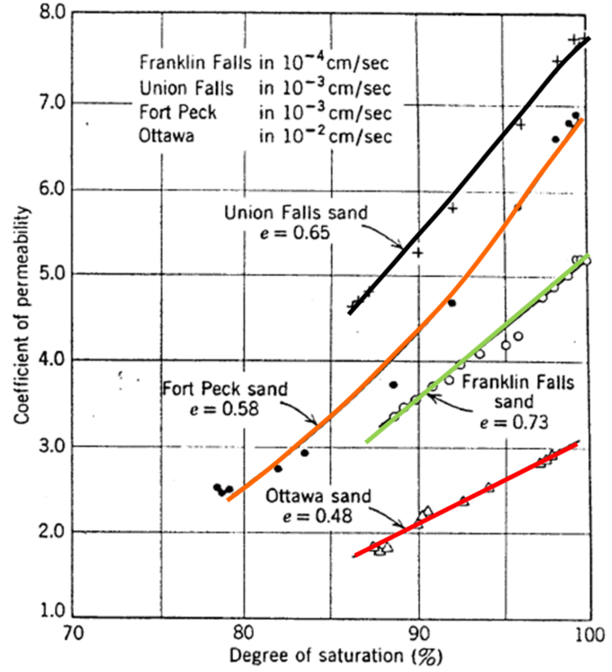


Lambe and Whitman, 1969

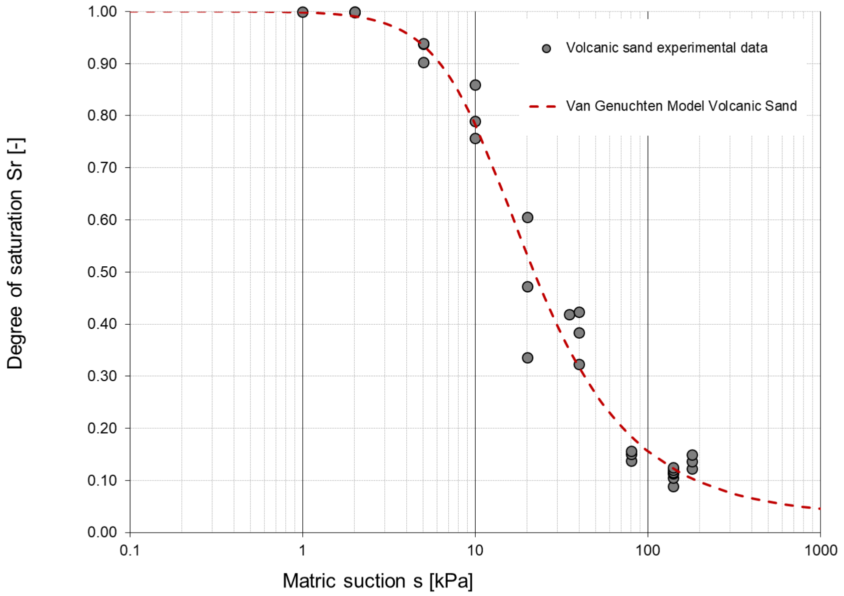
For an **unsaturated soil**, the **Darcy's law is still valid** but the coefficient of permeability depends on both the water content (or degree of saturation) and the void ratio.

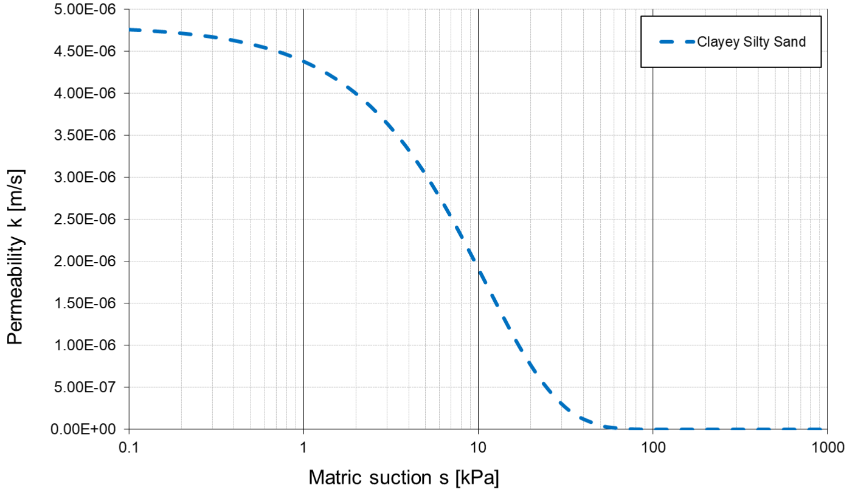
At higher degree of saturation, more connected pores are used by water to flow

For a given void ratio, the higher the degree of saturation, the higher is the permeability coefficient



WRC and permeability





Van Genuchten, M., 1980

$$S_r = \left\{\frac{1}{1 + [\alpha(p_a - p_w)\,]^n}\right\}^m$$

α ,n, m fitting parameters

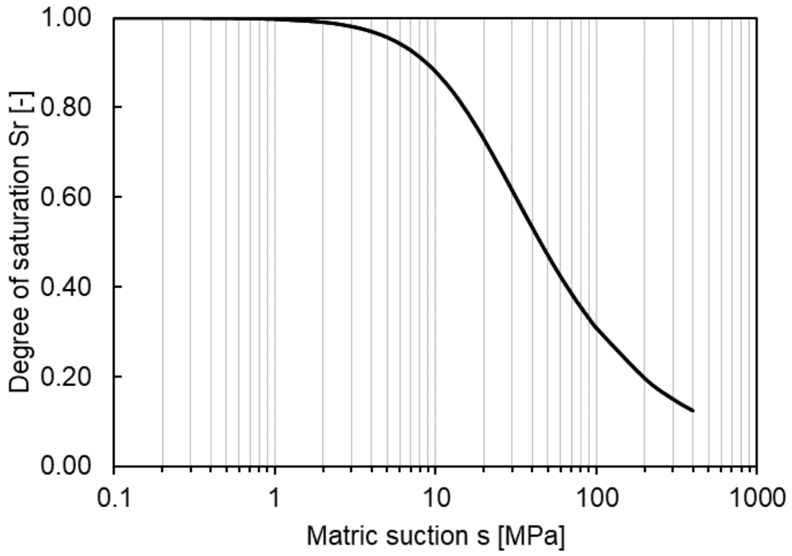
The evolution of the coefficient of permeability with suction can be described for example by using the Gardner's model (1958).

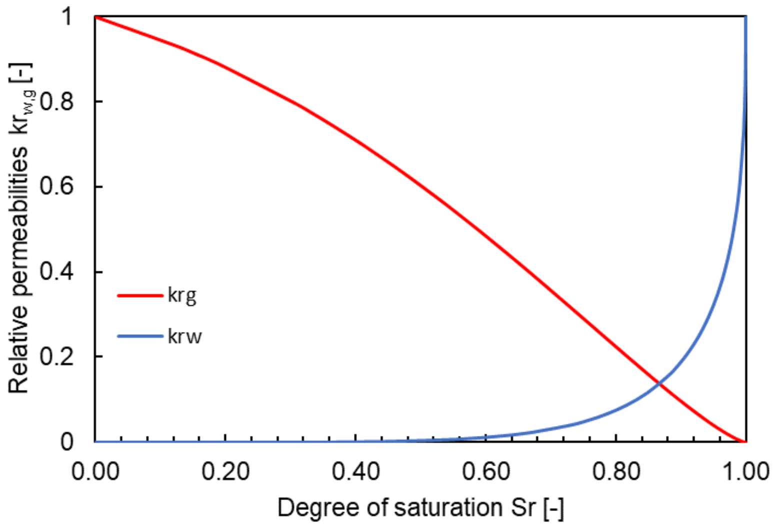
Gardner's model

$$k = k_{sat} e^{-\alpha(p_a - p_w)}$$

α fitting parameter

WRC and permeability





Van Genuchten, M., 1980

$$S_r = \left\{\frac{1}{1 + [\alpha(p_a - p_w)\,]^n}\right\}^m$$

α ,n, m fitting parameters

Mualem, Y. 1976

$$k_{rw} = \sqrt{S_r} \cdot \left[1 - \left(1 - S_r^{\frac{1}{m}}\right)^m\right]^2$$

$$k_{rg} = \sqrt{1 - S_r} \cdot \left[1 - S_r^{\frac{1}{m}}\right]^{2\mathrm{m}}$$

m fitting parameter

Generalized Darcy’s law for partially saturated porous media
Flux for a given fluid *i*, $\mathbf{q}_\mathrm{i}$

$$\boldsymbol{q_i} = -\frac{\boldsymbol{k_i}}{\mu_i}(\boldsymbol{\nabla} p_i + \rho_i \boldsymbol{g})$$

$$\boldsymbol{k}_i = \boldsymbol{K} k_{r,i}(S_r)$$

k: *apparent permeability*
μ: dynamic viscosity
p: pressure
ρ: density
g: *gravity*

The intrinsic permeability ***K***, is scaled by the relative permeability of the considered fluid *i*: $k_{r,i}$ *fct*(Sr_i)

Mechanical behaviour of unsaturated geomaterials

NET STRESS AND GENERALIZED EFFECTIVE STRESS

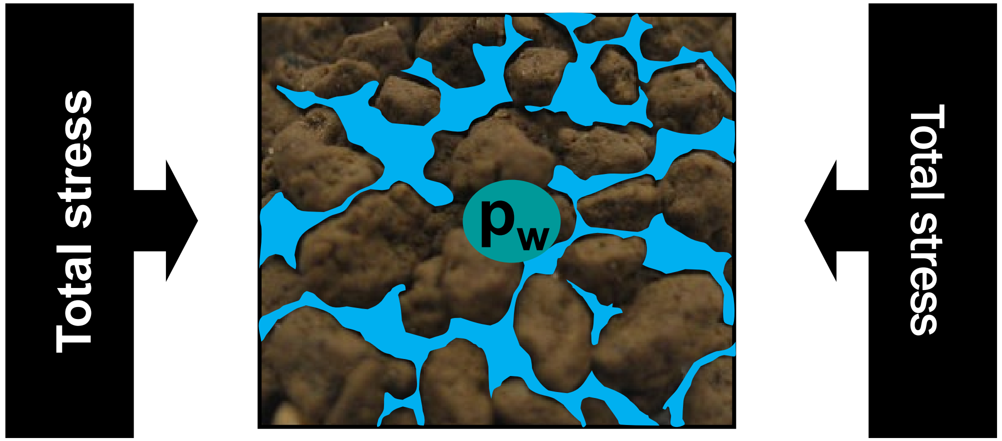
VOLUMETRIC BEHAVIOUR AND WETTING COLLAPSE

SHEAR STRENGTH

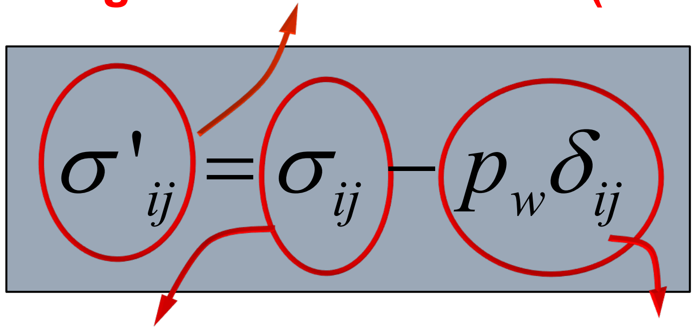
SWELLING SOILS & DESICCATION CRACKS

Suction, net stress and effective stress

We have seen that in the case of **saturated specimens** with incompressible water and solid grains the effective stress is



Terzaghi's effective stress (1936):



$$\sigma'_{ij} = \sigma_{ij} - p_w \delta_{ij}$$

Total stress

Porewater pressure

SUCTION

The difference between the pressure of the air and the pressure of the water

$$s = p_a - p_w = \frac{2T\cos\theta}{r}$$

$s\delta_{ij}$ **suction stress tensor**

NET STRESS

The difference between the external stress and the air pressure

$$\sigma_{net,ij} = \sigma_{ij} - p_a \delta_{ij}$$

net stress tensor

Suction, net stress and effective stress

If the **porewater pressure is negative (suction > 0)**, two different situations must be distinguished:

Quasi-saturated state $s < s_{AEV}$ ($S_r=1$)

Even if the pore water pressure is negative, the soil remains close to saturated

$$\sigma'_{ij} = \sigma_{ij} - p_w \delta_{ij}$$ It is still valid

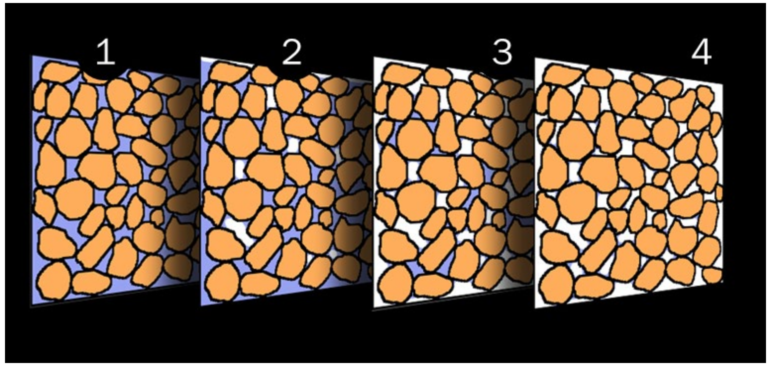
$$\Rightarrow \sigma'_{ij} = \sigma_{ij} + |p_w| \delta_{ij}$$

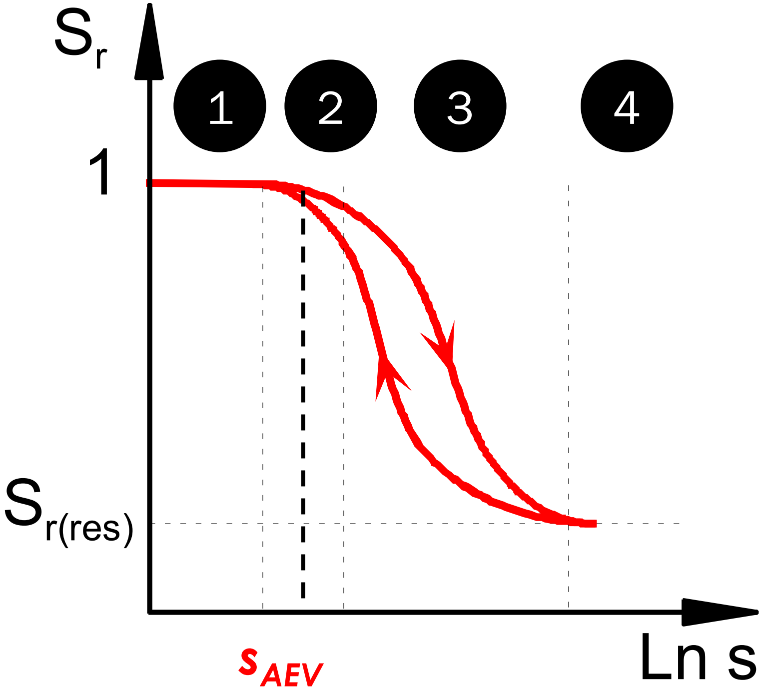
Partially saturated state $s > s_{AEV}$ ($S_r<1$)

The pore water pressure is negative and the soil is partially saturated

The effective stress concept needs to be generalized:

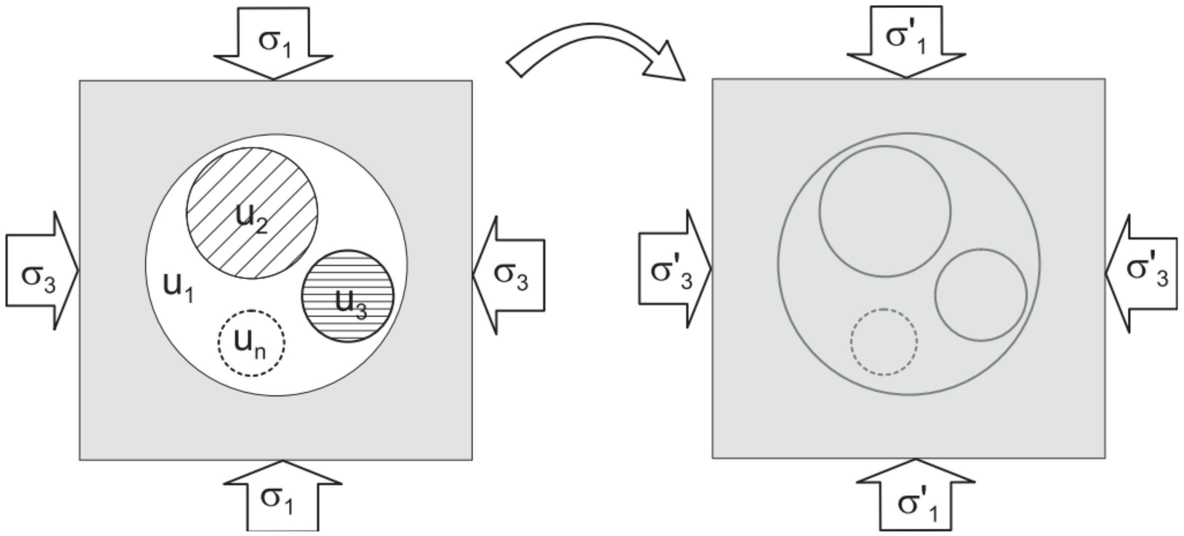
$$\Rightarrow \sigma'_{ij} = \sigma_{ij} - p_{equivalent} \delta_{ij}$$





Suction, net stress and effective stress

The effective stress with more than one fluid



Conversion of a multiphase and multi stress medium in an equivalent medium

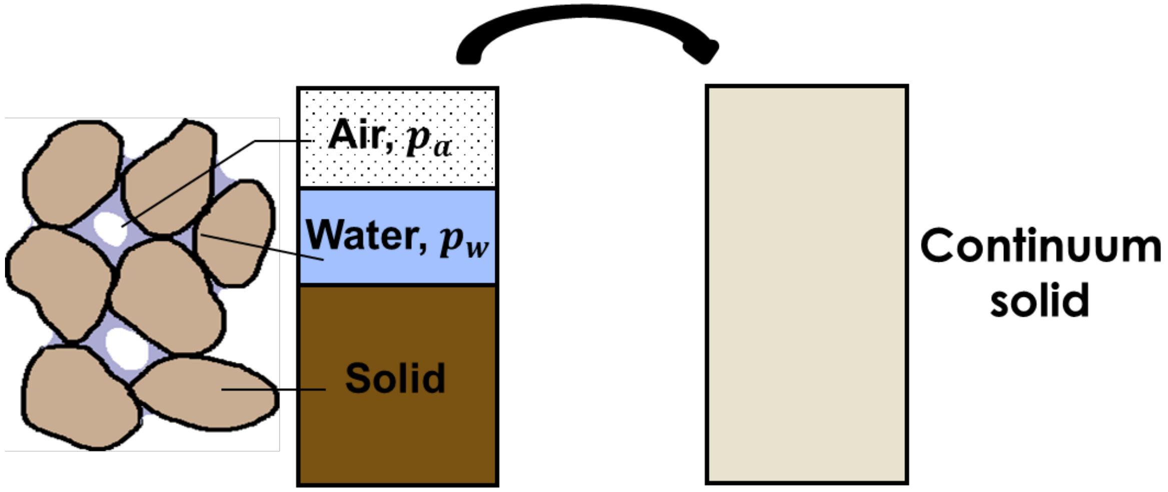
For many geomaterials the following general expression of effective stress is valid

$$\sigma'_{ij} = \sigma_{ij} - \sum_{\beta=1}^{i} \alpha_\beta p_\beta \delta_{ij}$$

σ_{ij} : total stress
β: generic fluid
α_β: scaling factor of the fluid β
p_β: pressure of the fluid β

Suction, net stress and effective stress

The effective stress in the specific case of unsaturated soils



Multi-phase description

Single-phase description

$$\sigma'_{ij} = \sigma_{ij} - \sum_{\beta=1}^{2} \alpha_\beta p_\beta \delta_{ij}$$

$$\Downarrow$$

$$\sigma'_{ij} = \sigma_{ij} - (1-\chi) p_a \delta_{ij} - \chi p_w \delta_{ij}$$

$$\sigma'_{ij} = (\sigma_{ij} - p_a \delta_{ij}) + \chi (p_a - p_w)\, \delta_{ij}$$

$$\sigma'_{ij} = \underbrace{\sigma_{net,ij}}_{\text{Net stress tensor}} + \underbrace{\chi s \delta_{ij}}_{\text{Suction stress tensor}}$$

with $\chi = f(S_r)$

if χ = Sr $\quad \sigma'_{ij} = \sigma_{net,ij} + Sr \cdot s\delta_{ij}$

Stress-strain variables

Unsaturated soils

3 phases
- Gas phase (air)
- Liquid phase (water)
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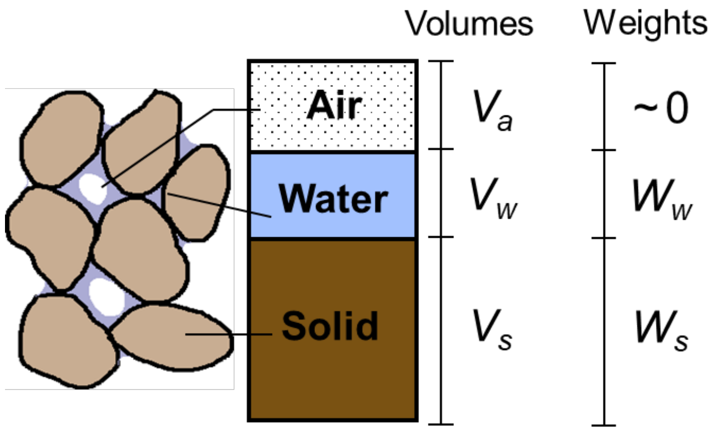
3 stress variables
- σ total mechanical stress
- p_w porewater pressure
- p_a pore-air pressure

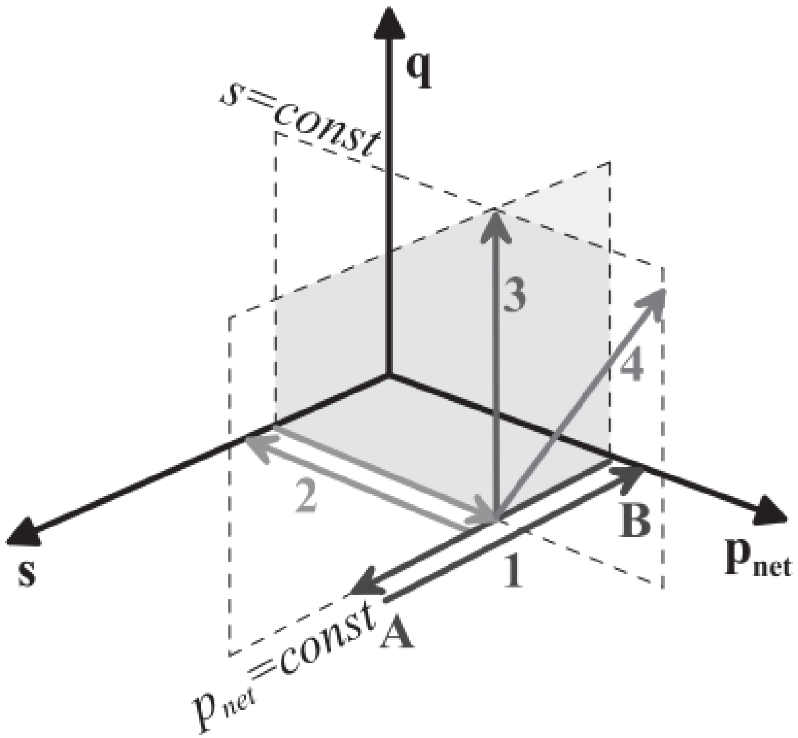


Three-phase description

A complete description of the rheological behaviour of unsaturated soils requires
- Soil water retention behaviour *How Sr changes for a given suction ?*
- Stress-strain behaviour *How the soil deforms?*

	Stress variables	Work-conjugate variables
Stress-strain variables for constitutive modelling of unsaturated soils	$\begin{pmatrix} \sigma' = \sigma_{net,ij} + Sr \cdot s\delta_{ij} \\ s \end{pmatrix}$	$\begin{pmatrix} \varepsilon \\ Sr \end{pmatrix}$

Possible stress paths



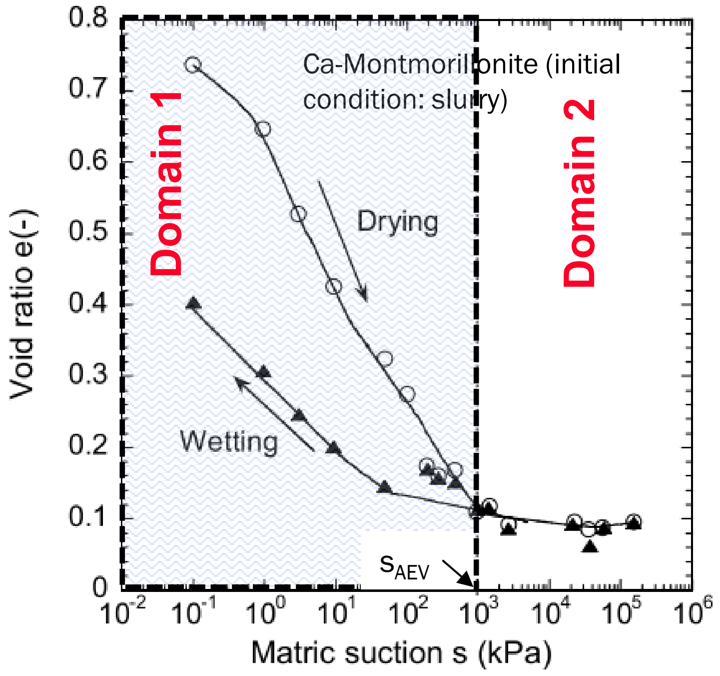
The possible stress paths to which a soil can be subjected can be highlighted in the 3D plane (s,p_{net},q)

Volumetric behaviour

Isotropic hydraulic loading (the suction is increased at a constant net stress)

Plane void ratio - suction

The **strains** induced by a drying or wetting process can be **elastic or elasto-plastic.** For some materials (usually if prepared from a slurry), we observe the following:

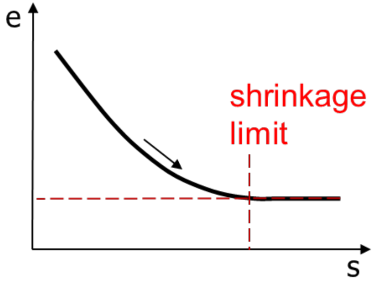


DOMAIN 1 – Elasto-plastic strains

If the suction is increased at a value lower than the air entry value and a wetting is performed, **NOT all the change in volume is recovered**

DOMAIN 2 – Elastic strains

If the suction is increased at a value higher than the air entry value and a wetting is performed, the **volume change** induced in the range of suction after the air entry value **is recovered**



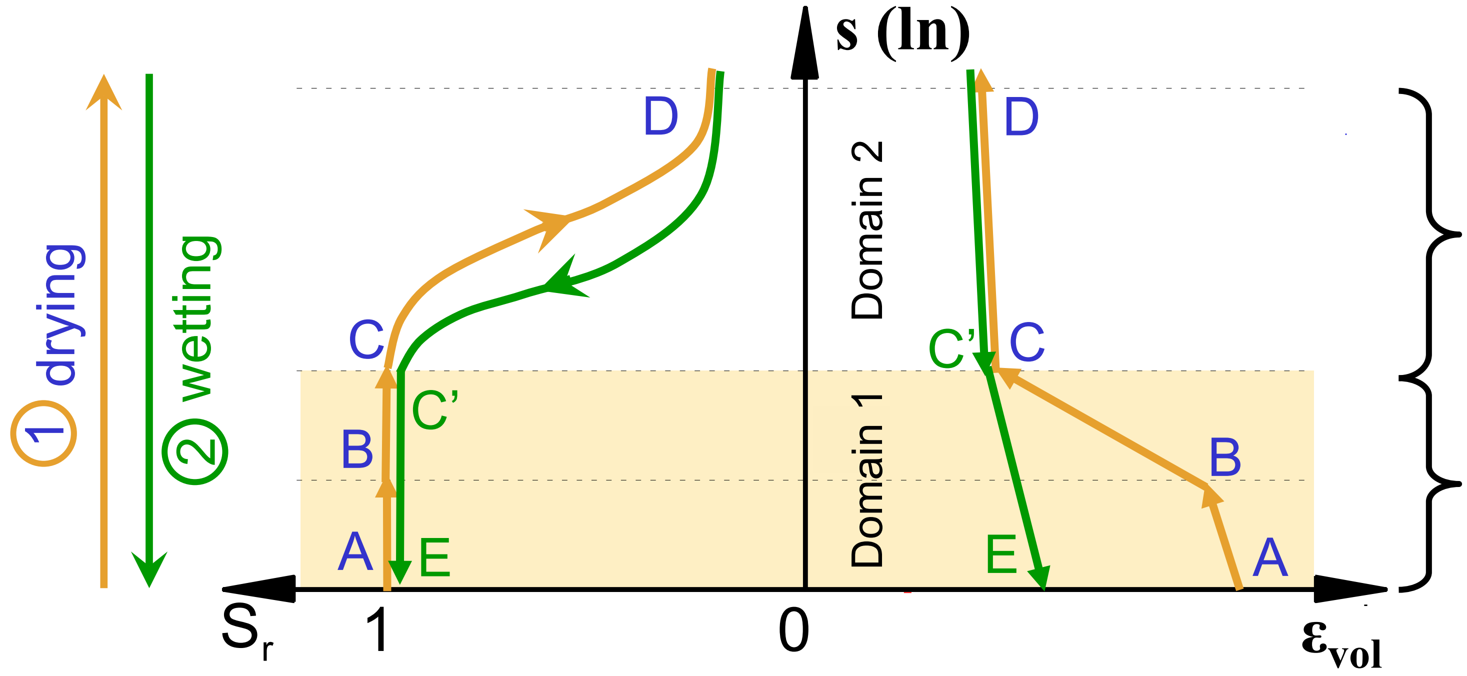
Shrinkage limit: value of suction starting from which no more significative variation in volume associated to an increase in suction are observed.

Volumetric behaviour

Isotropic hydraulic loading (the suction is increased at a constant net stress)

Plane suction-degree of saturation and suction-volumetric strain

The strains induced by a drying or wetting process can be elastic or elasto-plastic. For some materials (usually if prepared from a slurry), we observe the following:



$S_r<1$

$S_r=1$

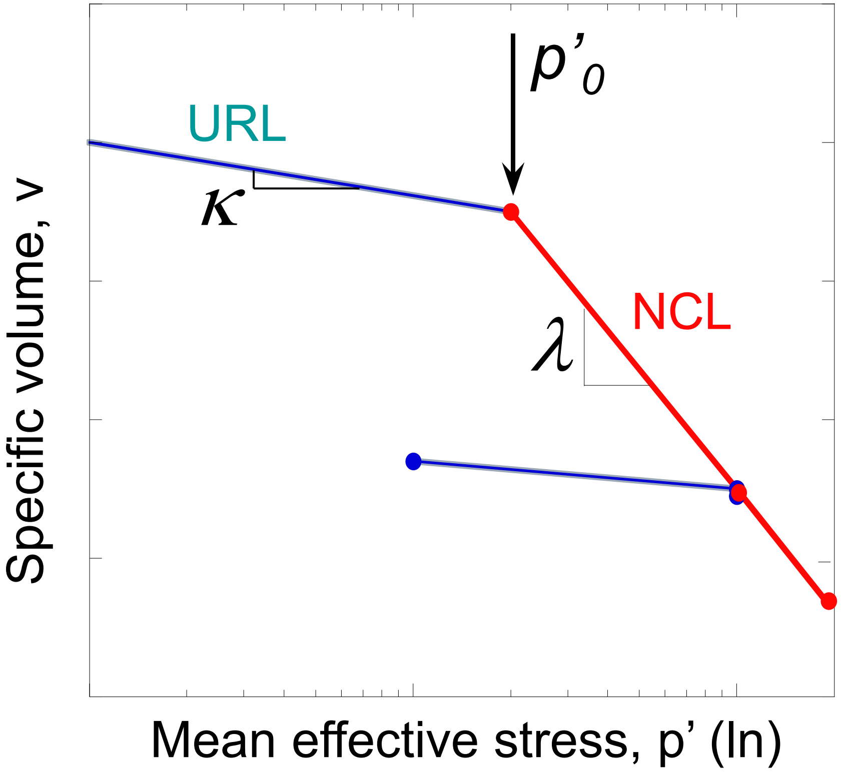
Domain 2
elastic strain

Domain 1
elasto-plastic strain

Volumetric behaviour

Isotropic mechanical loading – RECALL of the main equations and variables

Plane specific volume-mean effective stress



Normal Compression Line (NCL)

$$v = N - \lambda \ln p'$$

Unloading Reloading Line (URL)

$$v = v_k - k \ln p'$$

λ: slope of the NCL (plastic compressibility)
κ: slope of the URL (elastic compressibility)
N: specific volume at p'=1 in the adopted measurement system
ν_k: specific volume at p'=1 in the adopted measurement system

p'_0: Preconsolidation pressure

Volumetric behaviour

Isotropic mechanical loading at constant suction

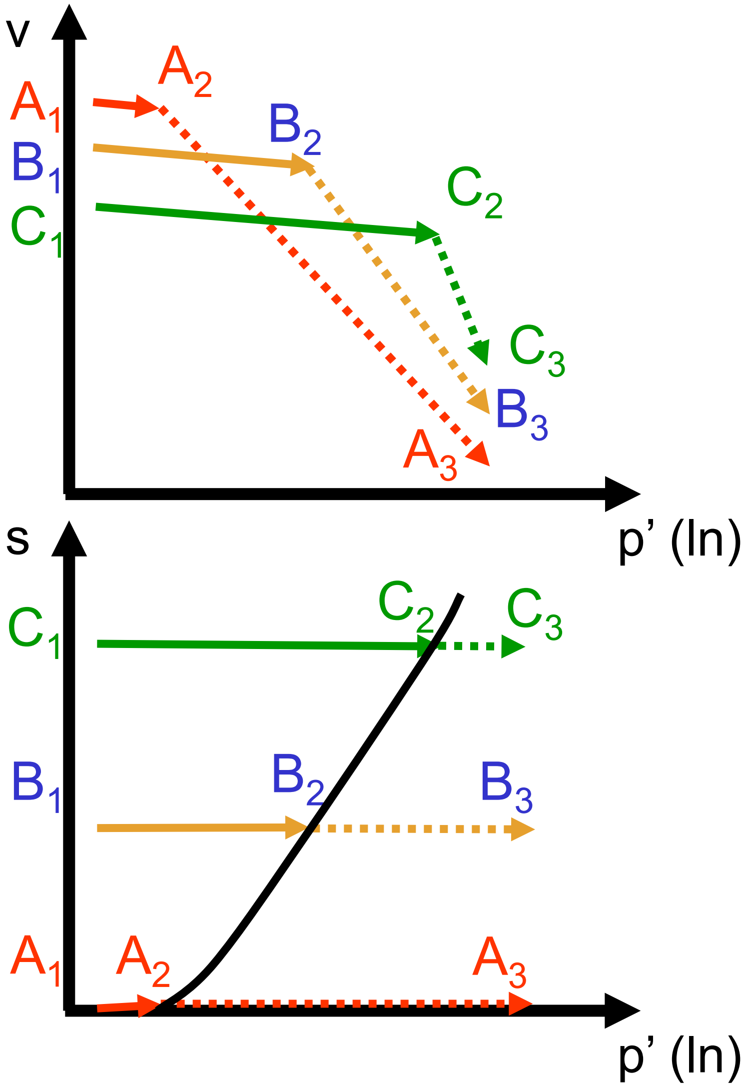
Plane specific volume-mean effective stress

An increase of suction implies:

- an increase of the preconsolidation pressure (apparent hardening)
- a variation of the plastic compressibility
- elastic compressibility remains constant

Points A_2, B_2 and C_2 delimit the elastic domain for each path

The curve connecting all the preconsolidation pressure at the different suction values is the yield locus in the plane (s-p'). It is called **Loading-Collapse curve (LC).**

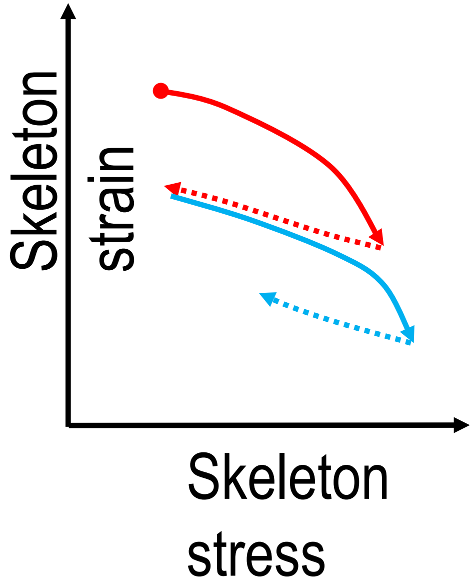


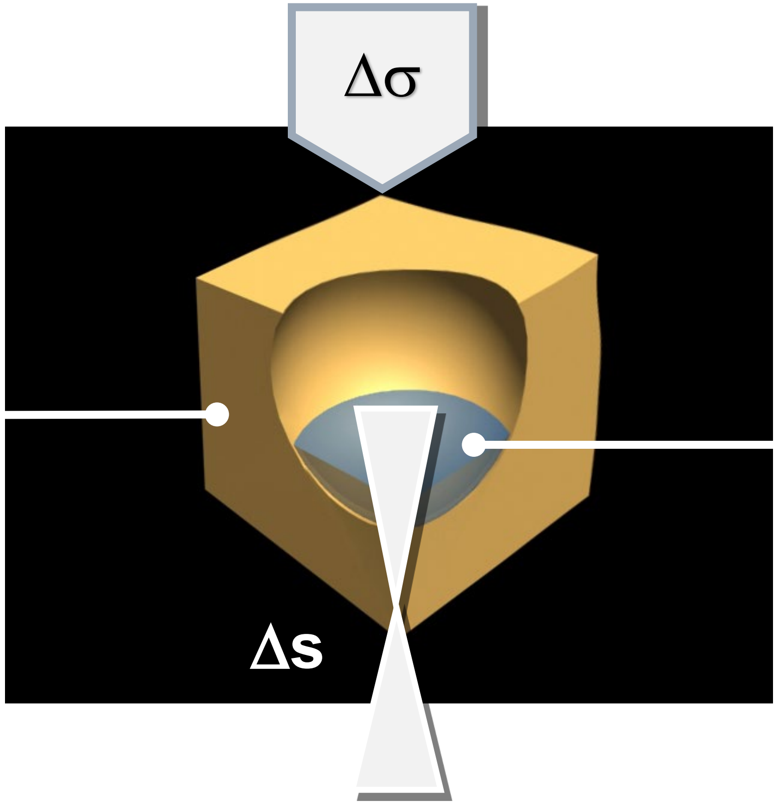
Volumetric behaviour

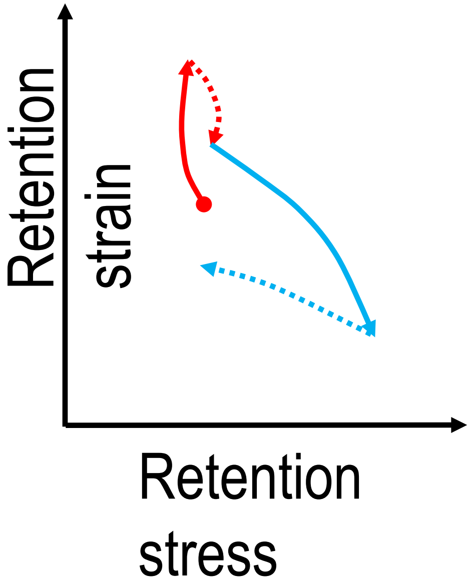
Skeleton straining and **saturation changes** are a response to

(a) External mechanical loading σ

(b) Variations in suction s





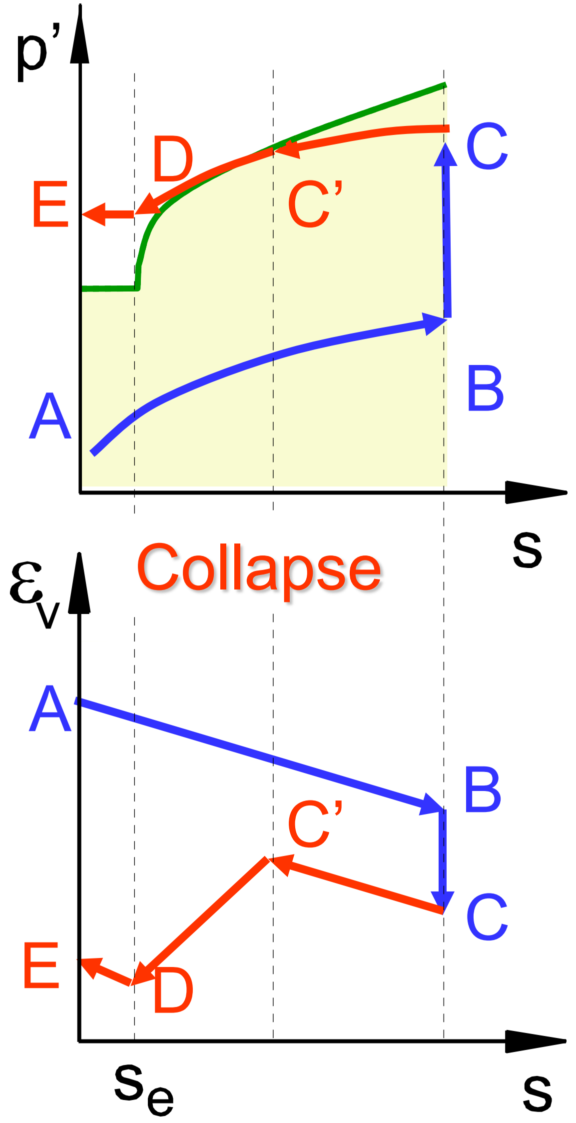


Irreversible processes in both cases

Wetting collapse

- AB: **drying** (p=const.)
- BC: mechanical **consolidation** (s=const.)
- CC': wetting – elastic **swelling**
- C'D: wetting – **plastic collapse**
- DE: wetting – elastic **swelling**

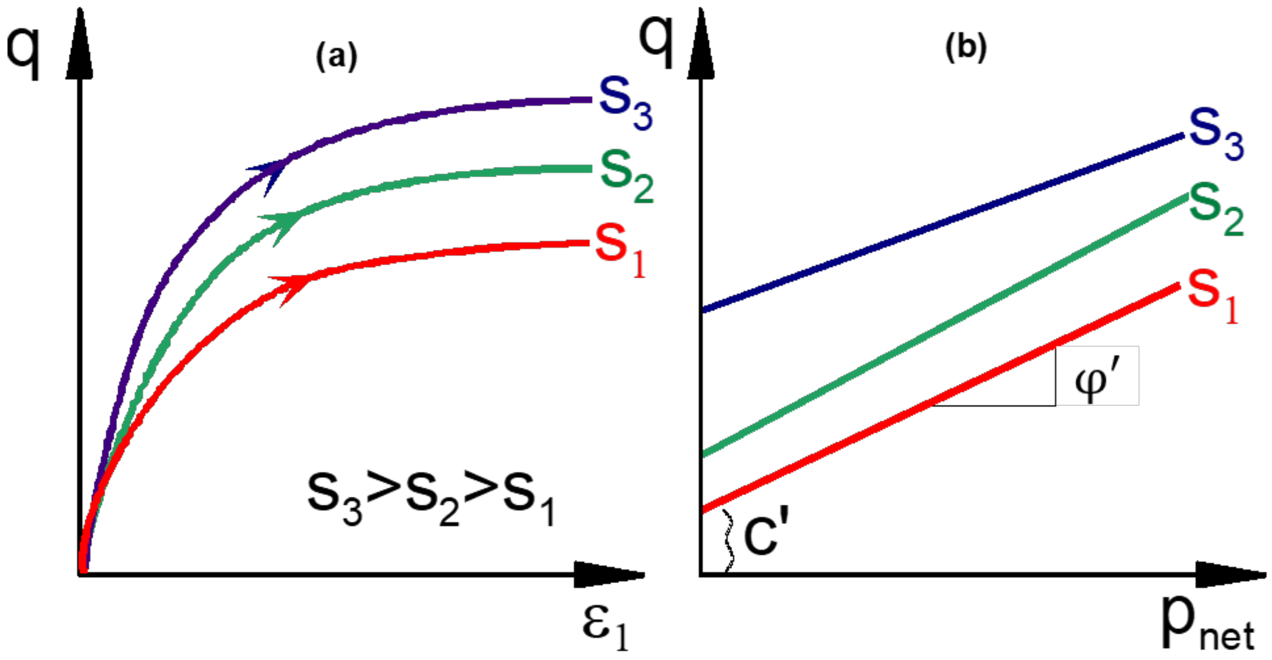
LC curve 🟨 Elastic domain



Shear strength

Deviatoric mechanical loading at constant suction

Planes q-ε_1 and q-p_{net}



Effects of suction on the shear strength

An increase of suction implies

- an increase of the cohesion intercept c’
- a variation of the shear strength angle φ’
- an increase of the overall shear strength

Shear strength

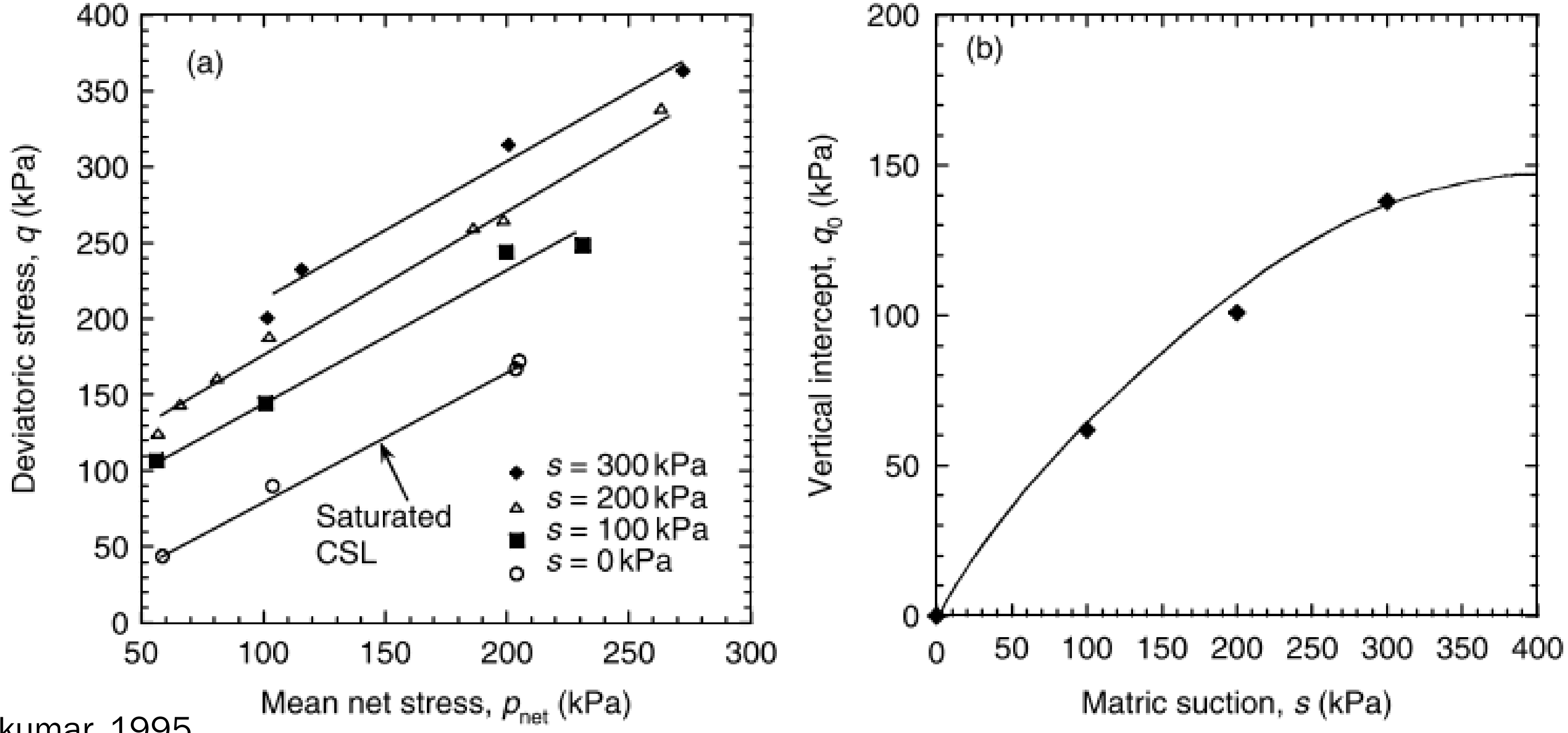
<u>Deviatoric mechanical loading at constant suction</u>

Planes q-p_{net}

q_0 as function of suction

Effects of suction on the shear strength

- *Apparent* cohesion is suction dependent
- Friction angle remains fairly constant
- Increase of the overall shear strength



Data from Wheeler & Sivakumar, 1995

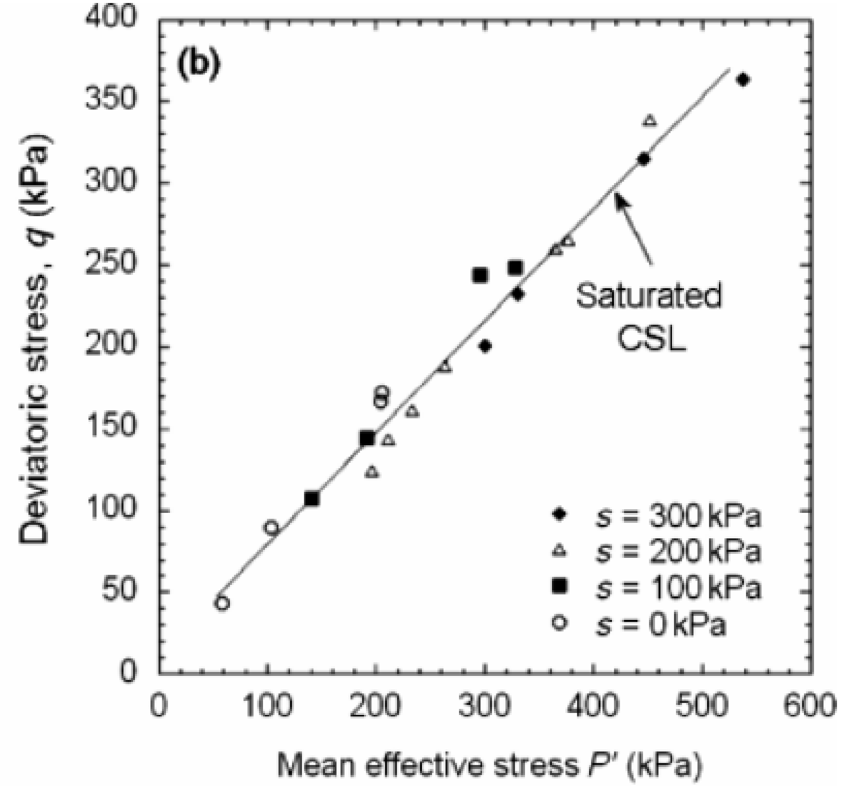
Shear strength

Deviatoric mechanical loading at constant suction

Planes q-p'

$$p' = p_{net} + S_r s$$

$$p_{net} = p - p_a \qquad p = \frac{\sigma_1 + \sigma_2 + \sigma_3}{3}$$



Data from Sivakumar, 1995

The adoption of a **suitable definition of effective stress** allows defining a **unique shear strength envelope** irrespective of the degree of saturation of the soil.

An increase of the mean effective stress, related to an increase in **suction** and/or an increase of the **mechanical load,** results in an increase of the shear strength.

Shear strength

Deviatoric mechanical loading at constant suction

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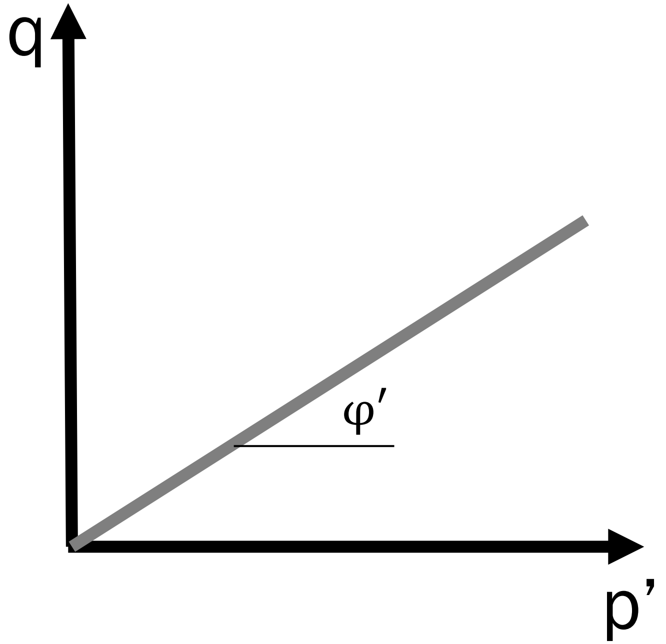


The adoption of a **suitable definition of effective stress** allows defining a **unique shear strength envelope** irrespective of the degree of saturation of the soil.

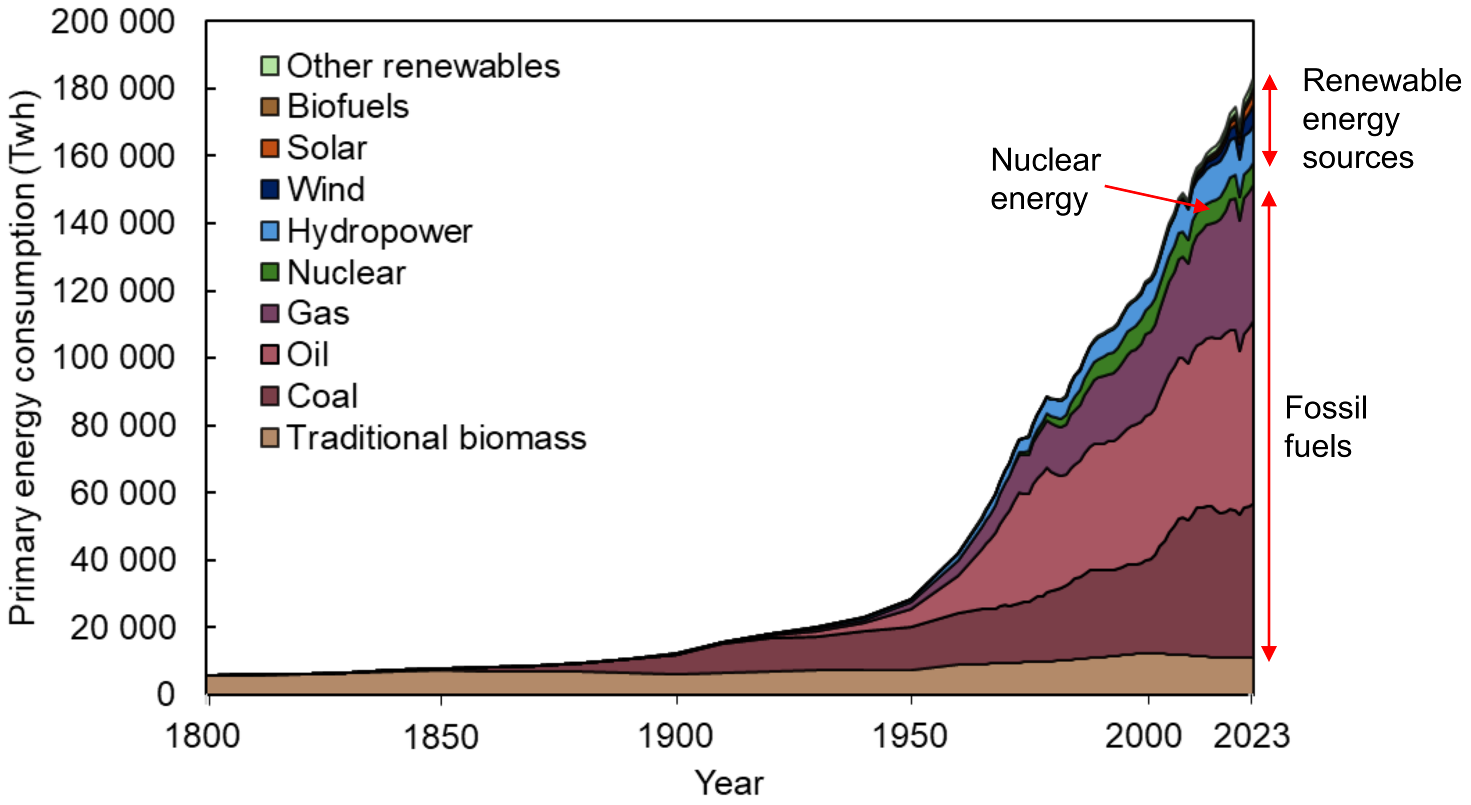
An increase of the mean effective stress, related to an increase in **suction** and/or an increase of the **mechanical load,** results in an increase of the shear strength

Conclusion

- **Unsaturated soils** are characterized by **two fluids and a solid phase**
- The **negative pore water pressure** is usually expressed in terms of **suction**
- The **water retention curve** describes the relationship between degree of saturation and suction
- The **Darcy's law is still valid** for unsaturated soils, the permeability is expressed in function of the degree of saturation
- The **Terzaghi's effective stress** is still valid if the pore water pressure is negative and the **degree of saturation is close to 1**. Otherwise, a more **general expression** has to be used
- The **volumetric behaviour and the shear strength** of a soil are affected by variation in suction

Unsaturated geomaterials in the context of nuclear waste disposal

Nuclear energy



Worldwide primary energy consumption in terawatt-hours (Twh)
Data source: Energy Institute - Statistical Review of World Energy (2024); Smil (2017)

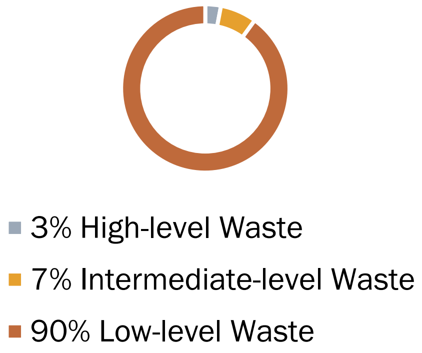
Energy has shaped human development

Nuclear energy accounts for 10% of worldwide electricity production (~32% in CH)

Significant challenges

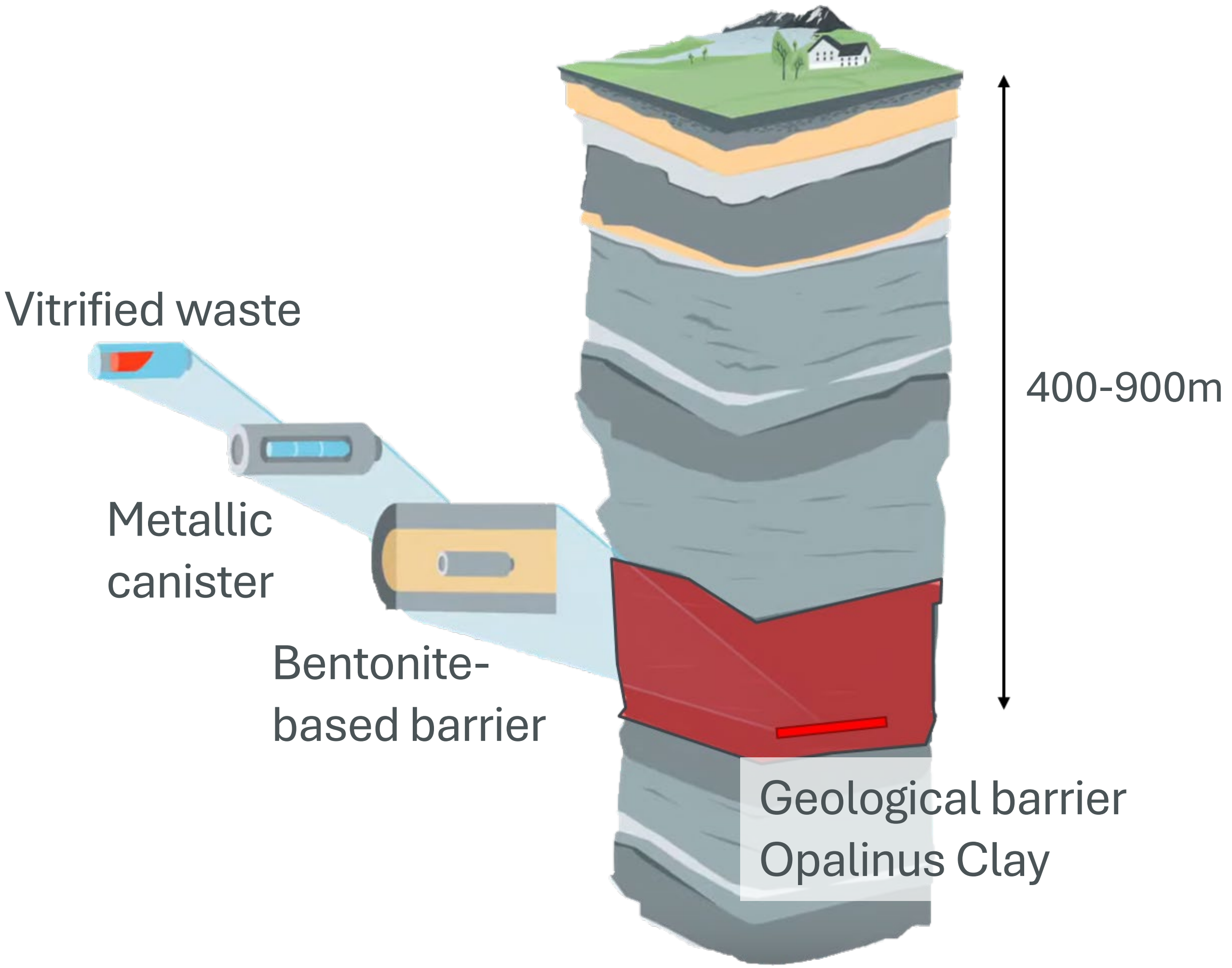
- Risk of accidents (reduced by advances in technology)
- Radioactive waste management

Types of Nuclear Waste



Source: World Nuclear Association

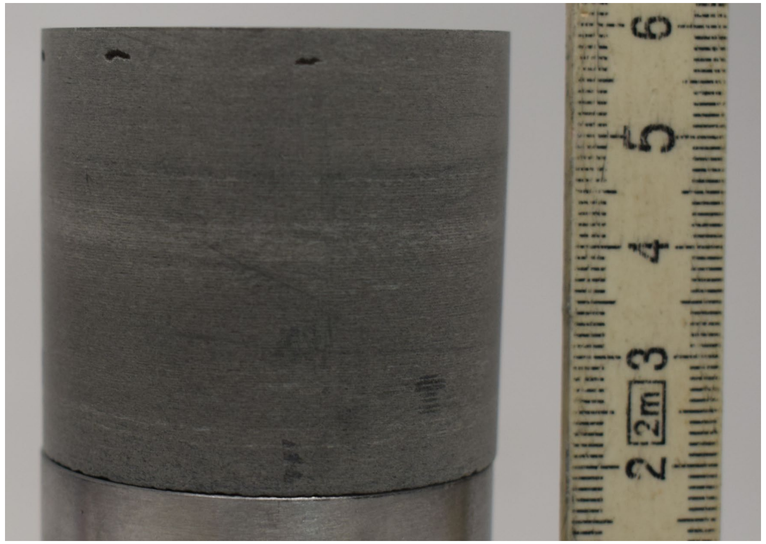
Swiss concept - Multi-barrier system



Nagra

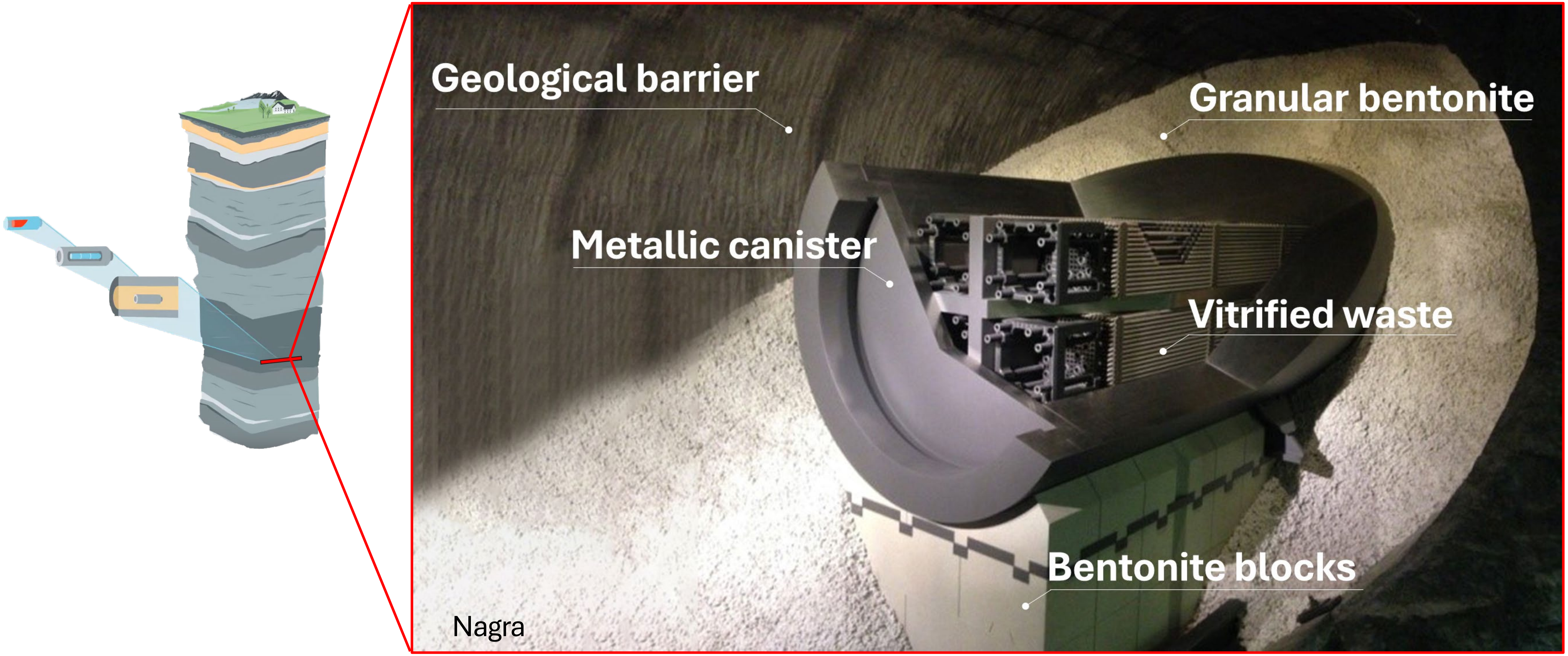
Opalinus Clay shale

- *Low permeability: 10^{-19}-10^{-21} m^2*
- *Self-sealing capacity*
- *High retention of radionuclides*



Picture of Opalinus Clay sample for triaxial test (EPFL/LMS)

Swiss concept - Multi-barrier system



Nagra

Long-term multi-physical processes

Excavation

Stress redistribution

~1
year

Ventilation

Consolidation
Desaturation

~10
years

Early-time

Hydration from the far field
Heating from the canister

~100
years

Late-time

Isothermal conditions
restored

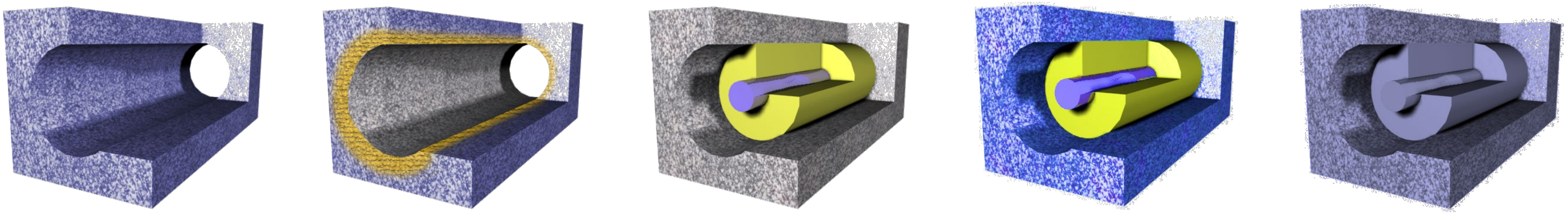
~1000
years

**Gas generation
and migration**

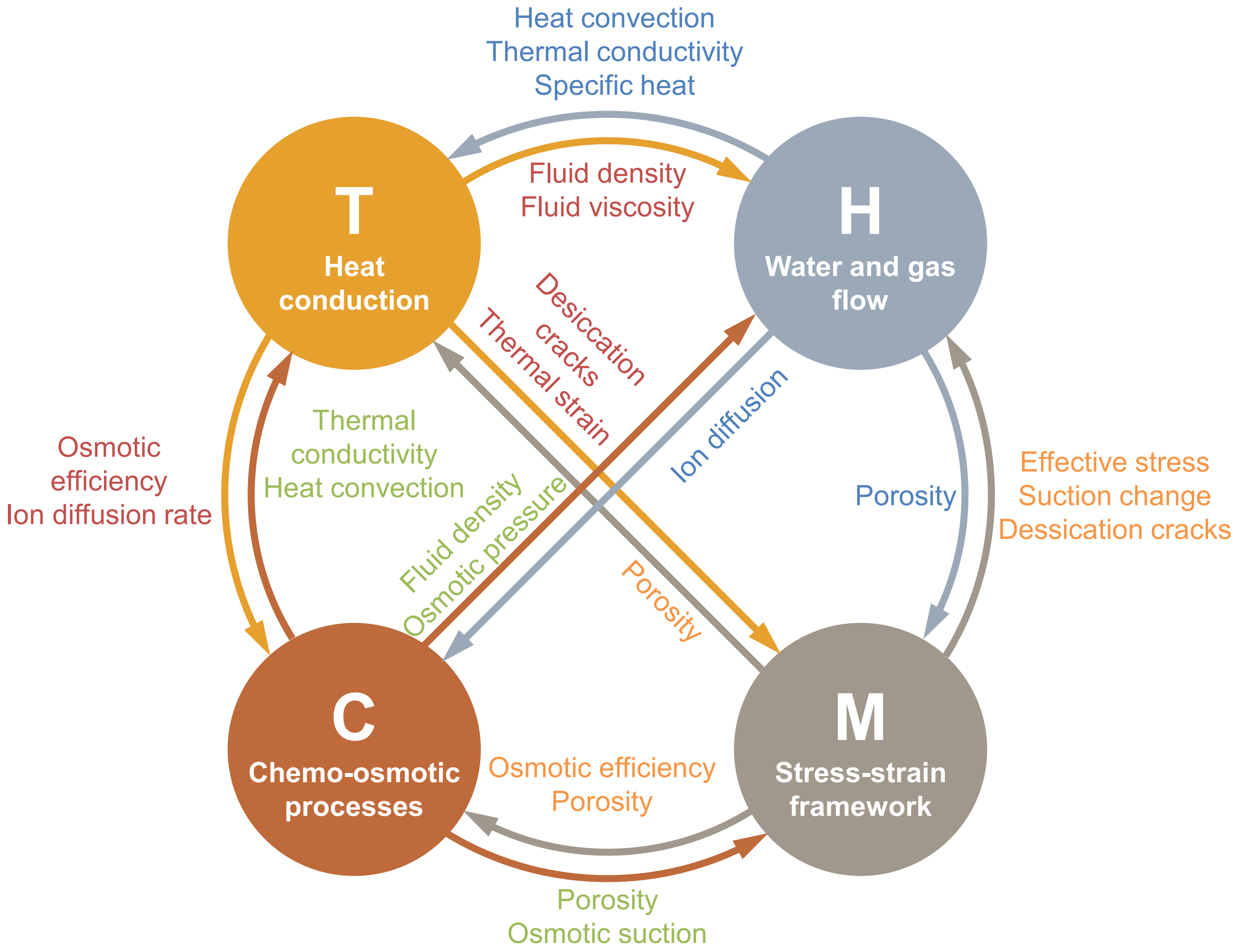
Very-late-time

Towards a THM
equilibrium

~10,000
years



Overview of interacting phenomena in a repository



T
Heat conduction

H
Water and gas flow

C
Chemo-osmotic processes

M
Stress-strain framework

Heat convection
Thermal conductivity
Specific heat

Fluid density
Fluid viscosity

Desiccation cracks

Thermal strain

Ion diffusion

Osmotic efficiency
Ion diffusion rate

Thermal conductivity
Heat convection

Fluid density
Osmotic pressure

Porosity

Porosity

Effective stress
Suction change
Dessication cracks

Osmotic efficiency
Porosity

Porosity
Osmotic suction

(T)HM framework

- Compositional approach – mass balance of species:
  - Water, air and solid

- Primary state variables:
  - Medium displacement: $\mathbf{u}$
  - Water pressure: p_w
  - Gas pressure: p_a
  - Temperature: T

Balance equations

Mass balance of water (liquid water + vapour) - unknown: p_w

$$\frac{\partial}{\partial t}(\rho_w n S_r) + \mathrm{div}(\rho_w \mathbf{f}_l) - Q_w$$

$$+\frac{\partial}{\partial t}[\rho_v n(1 - S_r)] + \mathrm{div}\left(\mathbf{i}_v + \rho_v \mathbf{f}_g\right) - Q_v = 0$$

Mass balance of air (dry air + dissolved air) – unknown: p_a

$$\frac{\partial}{\partial t}[\rho_a n(1 - S_r)] + \mathrm{div}\left(\rho_a \mathbf{f}_g + \mathbf{i}_a\right) - Q_a$$

$$+\frac{\partial}{\partial t}[\rho_a H_s n S_r] + \mathrm{div}(\rho_a H_s \mathbf{f}_l) - Q_{da} = 0$$

Mass balance of solids (Lagrangian approach):

$$\frac{\partial}{\partial t}\rho_s(1 - n)V = 0$$

Internal energy balance of the medium – unknown: T

$$\frac{\partial S_T}{\partial t} + L\frac{\partial}{\partial t}[\rho_v n(1 - S_r)] + \mathrm{div}(\mathbf{f}_T)$$

$$+L \cdot \mathrm{div}\left(\mathbf{i}_v + \rho_v \mathbf{f}_g\right) - Q_T = 0$$

Momentum balance of the medium – unknown: $\mathbf{u}$

$$\mathrm{div}(\boldsymbol{\sigma}) + \mathbf{b} = \mathbf{0}$$

Constitutive equations

Liquid water flow

Darcy's Law:

$$\mathbf{f}_l = -\frac{k_w k_{rl}\mathbf{I}}{\mu}\text{grad}(p_w) \qquad k_{rl} = Sr^n$$

Kozeny-Carman Relation:

$$k_w = k_{w0}\frac{n^N}{(1-n)^M}\frac{(1-n_0)^M}{n_0^N}$$

Temperature dependent viscosity:

$$\mu_w = 0.6612(T-229)^{-1.562}$$

Vapour diffusion:

$$\mathbf{i}_v = n(1-S_r)\tau D\rho_g \text{grad}\left(\frac{\rho_a}{\rho_g}\right) = -\mathbf{i}_a \qquad D = 5.893\times 10^{-6}\frac{T^{2.3}}{p_g}$$

Heat flux:

$$\mathbf{f}_T = -\Gamma\text{grad}(T) +$$

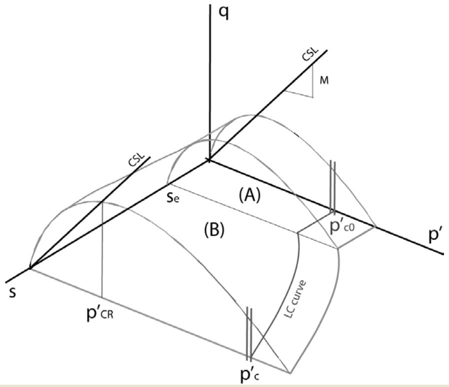
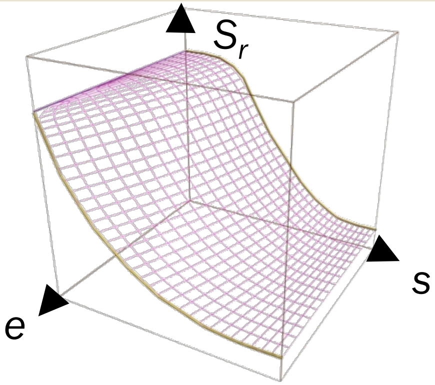
$$\left[c_{p,w}\rho_w\mathbf{f}_w + c_{p,a}\left(\mathbf{i}_a + \rho_a\mathbf{f}_g\right) + c_{p,v}\left(\mathbf{i}_v + \rho_v\mathbf{f}_g\right)\right](T-T_0)$$

Gas Pressure (ideal gas):

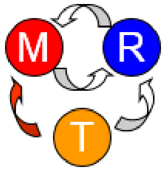
Dalton Law: $p_g = p_a + p_v$

$$\rho_a = \frac{p_a M_a}{RT} = \frac{(p_g - p_v)M_a}{RT} = \frac{p_g M_a}{RT} - \frac{\rho_v M_a}{M_v}$$

ACMEG-TS constitutive framework

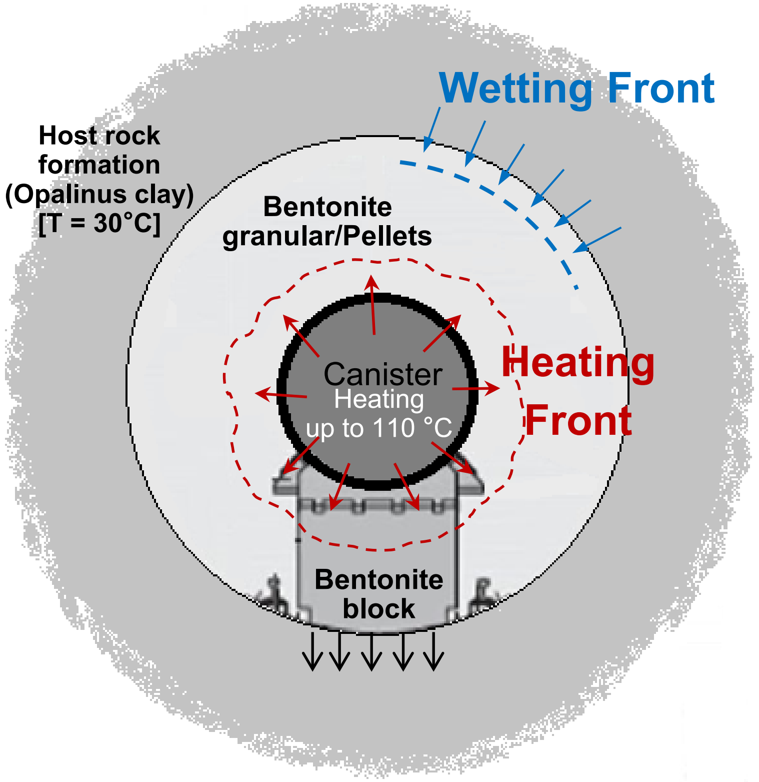
Modelled behaviour	Stress variable	Strain variable	Constitutive Relation
Mechanical  	$\sigma'_{ij} = \sigma_{net\,ij} + S_r s \cdot \delta_{ij}$ *Generalised effective stress*	ε_{ij} *Skeleton strain*	$d\sigma'_{ij} = D_{ijkl} : d\varepsilon_{kl}$ $d\sigma'_{ij} = \tilde{D}_{ijkl}(T):(d\varepsilon_{kl} - \beta_{kl} dT)$
Retention  	$s = (p_a - p_w)$ *Matric suction*	S_r *Degree of saturation*	$ds = A.dS_r$ $ds = A(T).dS_r$ *A:* Retention properties

+ Temperature



B. Francois and L. Laloui (2008)

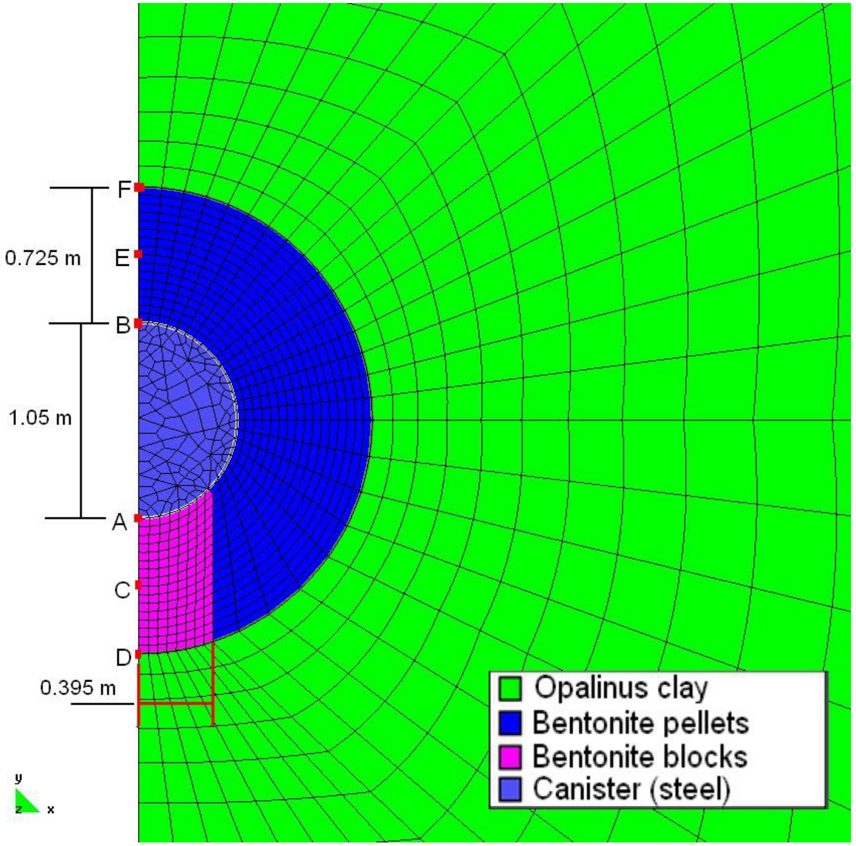
Field scale modelling



Heat emitting canister
Heating front

Water saturation
Wetting front

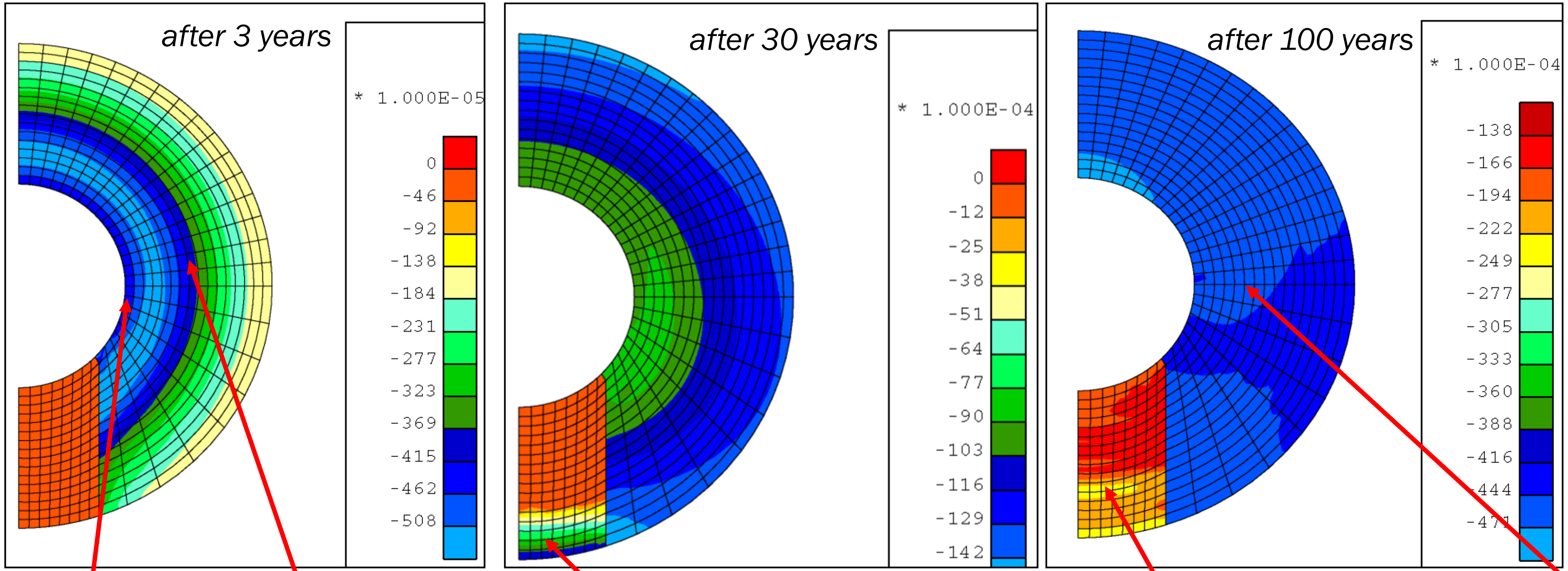
How heat and water transfer affect the mechanical behaviour of the buffer materials and the **canister movement**



Field scale modelling

Plasticity due to heat and/or suction change

Maps of Plastic Volumetric Strains, in m/m



Wetting collapse

Thermal collapse near the canister

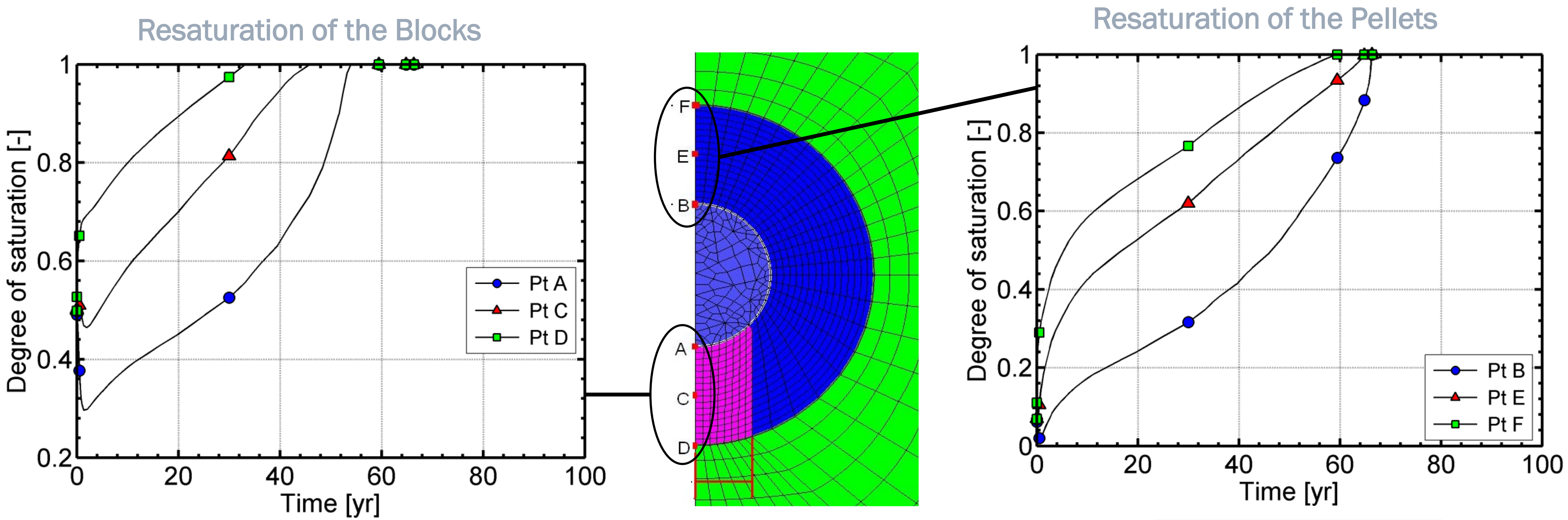
Onset of plasticity in the blocks due to wetting collapse

Evolution of wetting collapse in the blocks

Uniform plastic strain in the pellets

Field scale modelling

Resaturation of the bentonite buffer



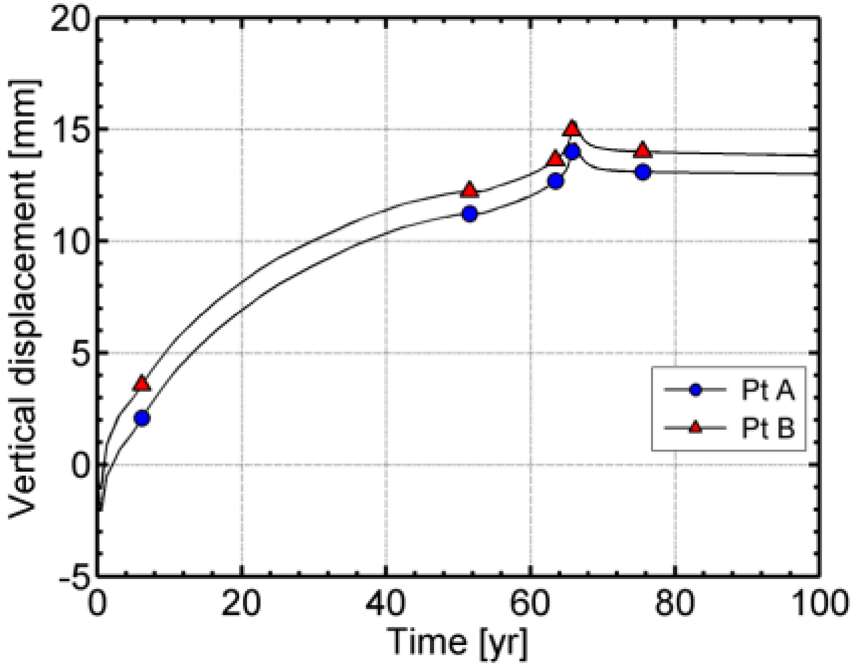
Resaturation of the Blocks

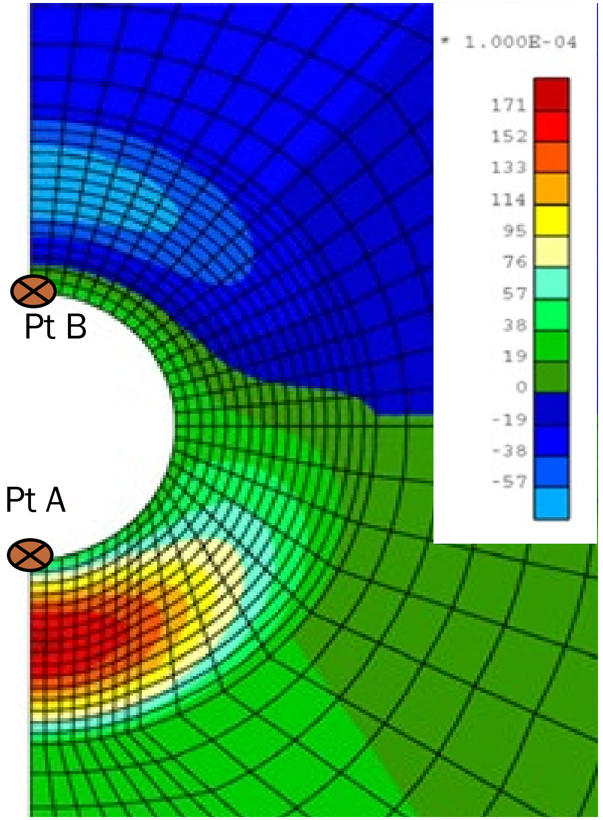
Resaturation of the Pellets

Pellets need additional 10-30 years to saturate.

Field scale modelling

Vertical displacement





Map of vertical displacement after 3 years, in m

Vertical movement of the canister

Bentonite swelling forces are stronger for blocks than for pellets

In this confined area, this competition creates an uplift of the canister

Thank you for your attention