# ALERT GEOMATERIALS

# New challenges and perspectives in modelling unsaturated soil behaviour

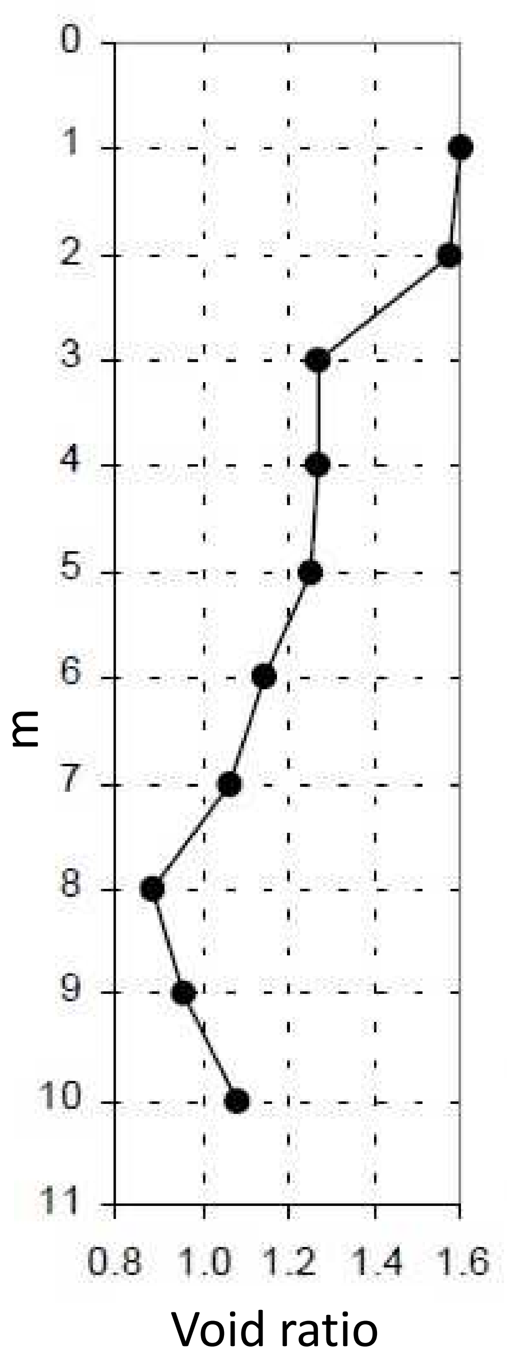

**E. E. Alonso**

Universitat Politècnica de Catalunya, Barcelona, Spain



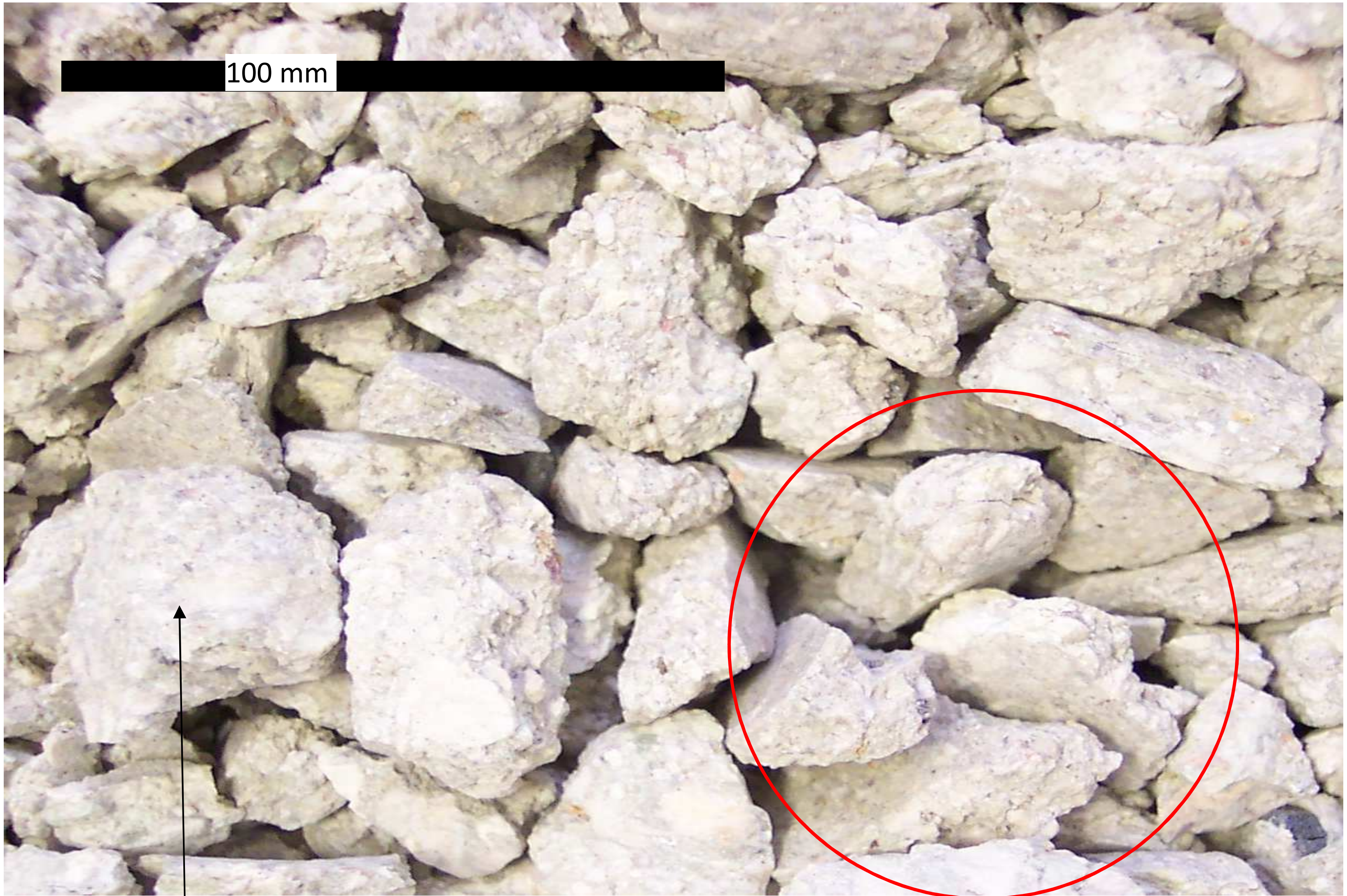
25th ALERT Workshop and School

Aussois, 29th September to 4th October 2014


0
1
2
3
4
5
6
7
8
9
10
11
m
0.8
1.0
1.2
1.4
1.6
Void ratio


Brasilia residual tropical soil

# PELLETS OF HIGHLY COMPACTED BENTONITE

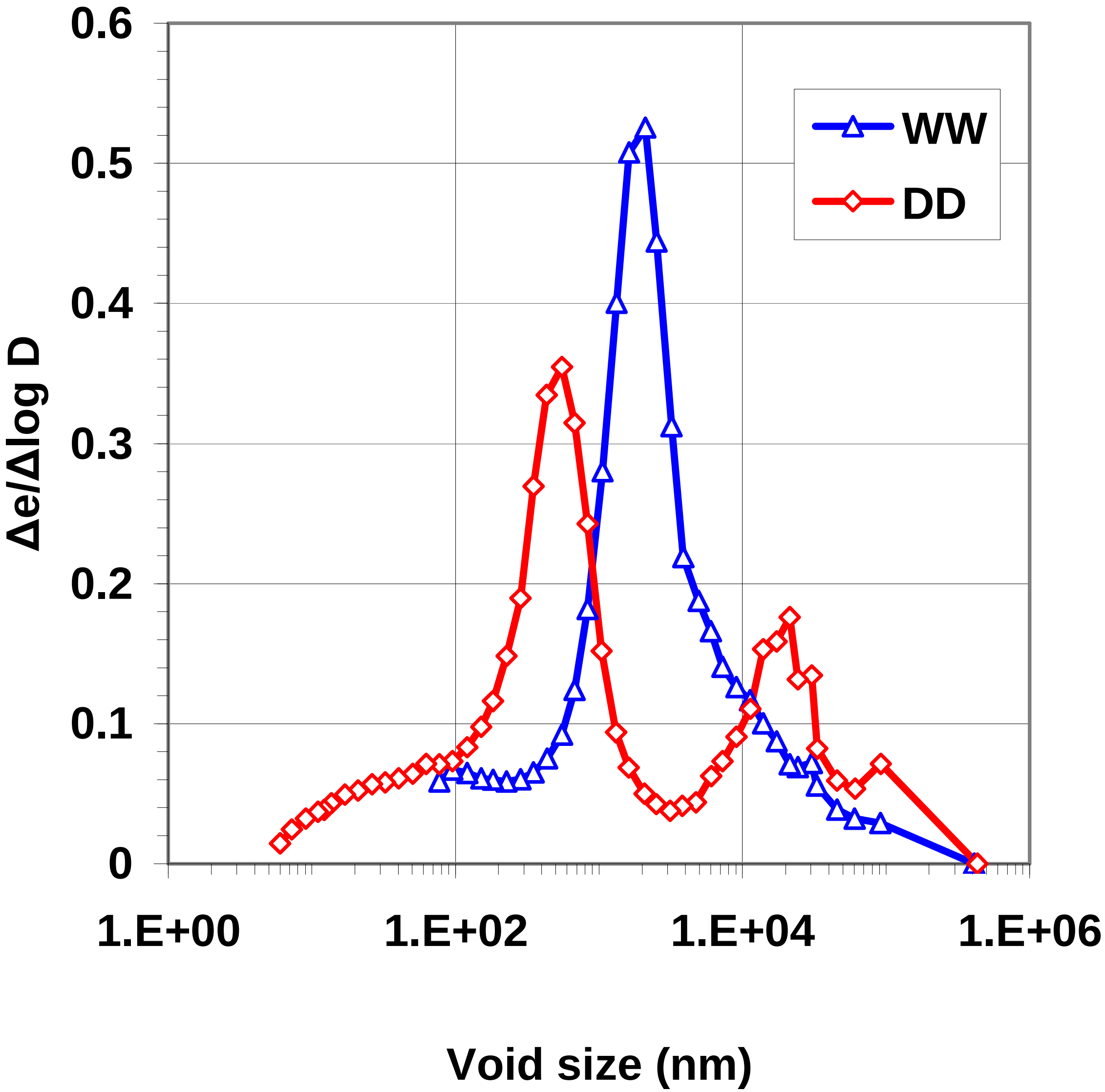



$\rho_d$ = 1.97 g/cc

$\rho_d$ = 1.36 g/cc


Pancrudo quartzitic
slate specimen at
RH = 90%

# Compacted soils

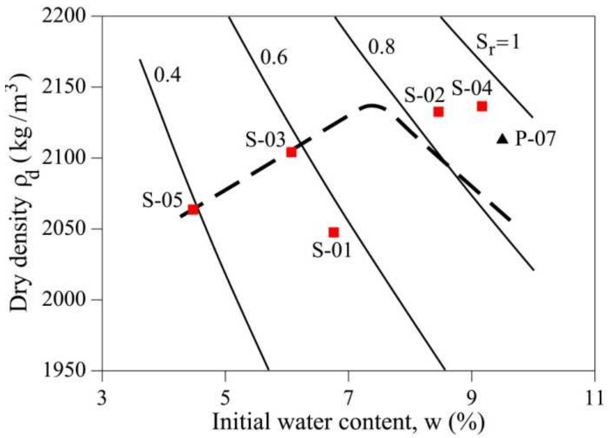


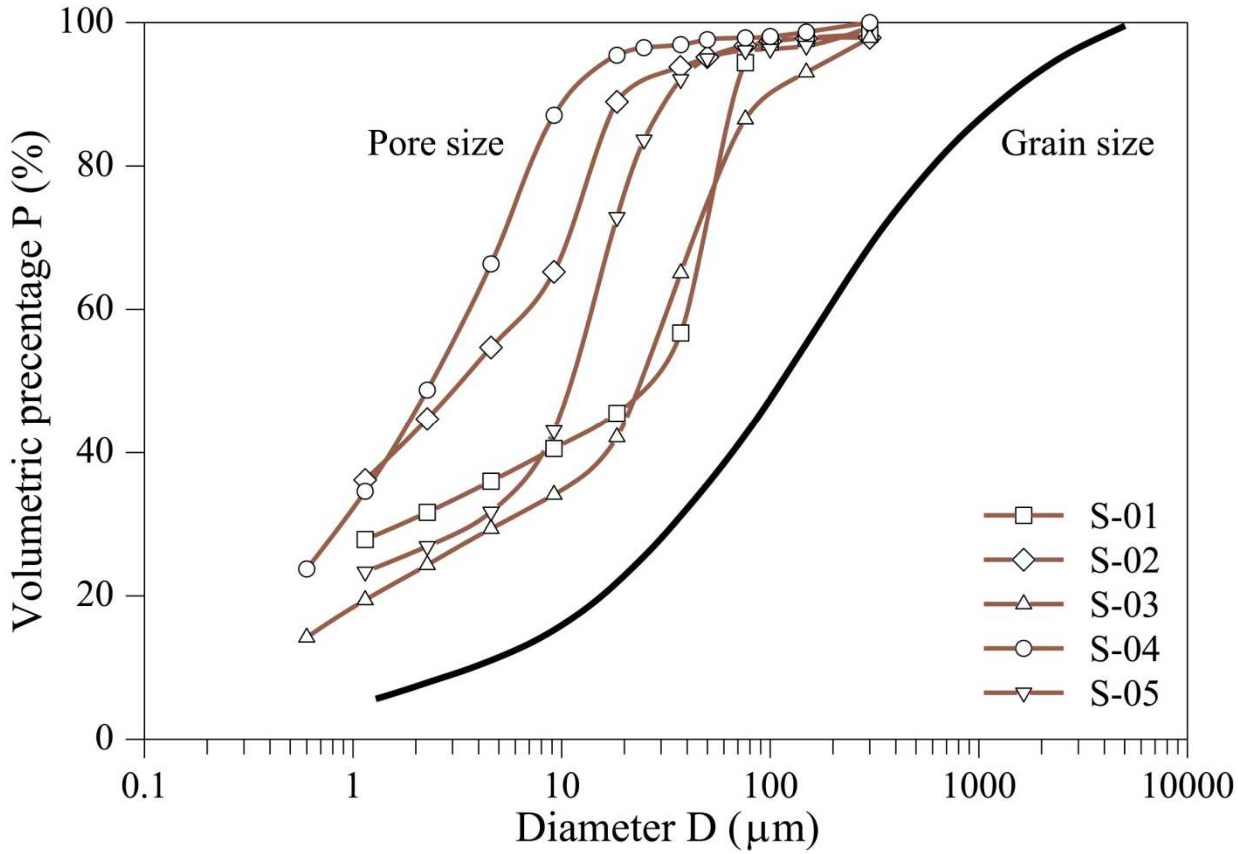

Barcelona red silty clay. MIP wet and dry of optimum

- Microstructure
- Effective stress fields and constitutive modelling
- Local equilibrium of suction

- Microstructure

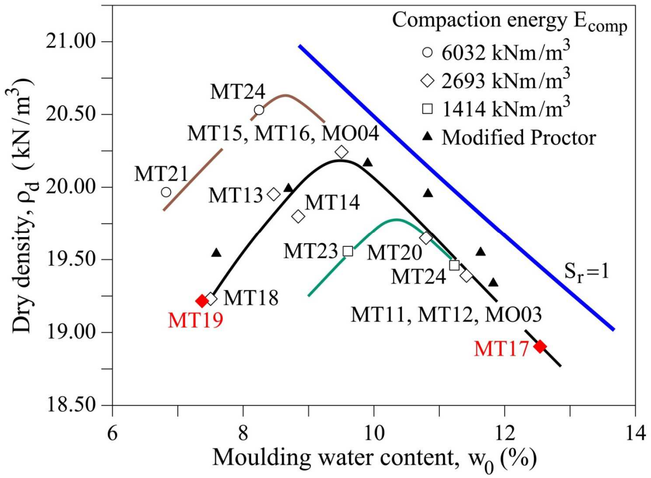
- Pore size and grain size distribution. Non-plastic glacial till
- A widely different distribution of pore sizes for a given grain size distribution, even for a non-plastic material

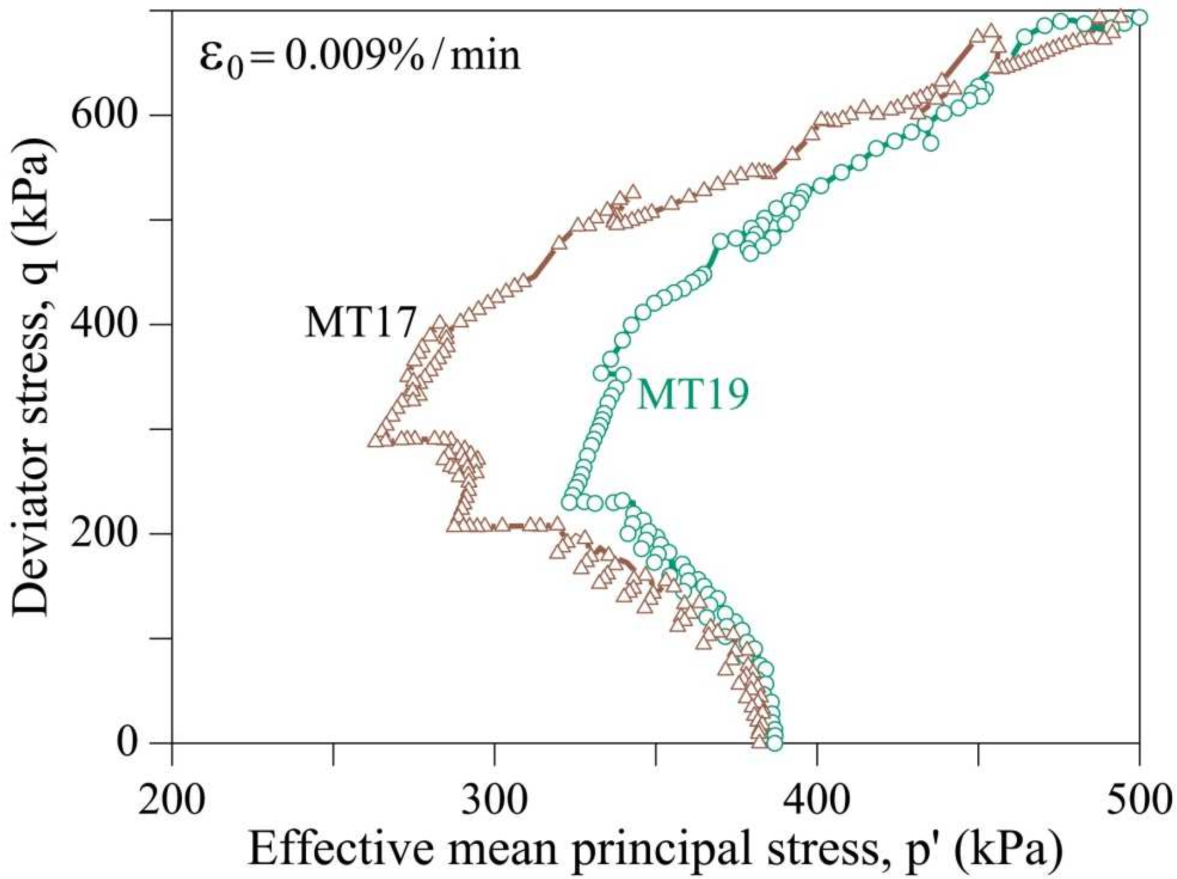



*(Watabe, Leroueil and Le Bihan, 2000)*

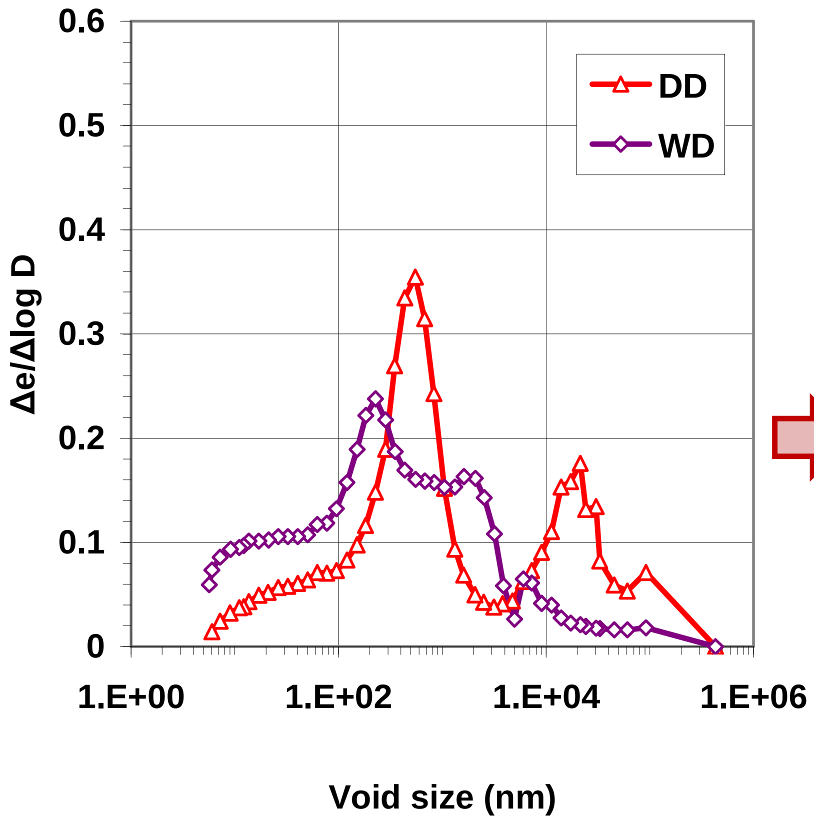
- Stress-strain behaviour of compacted silty sand under saturated conditions
- **Strength, undrained loading**

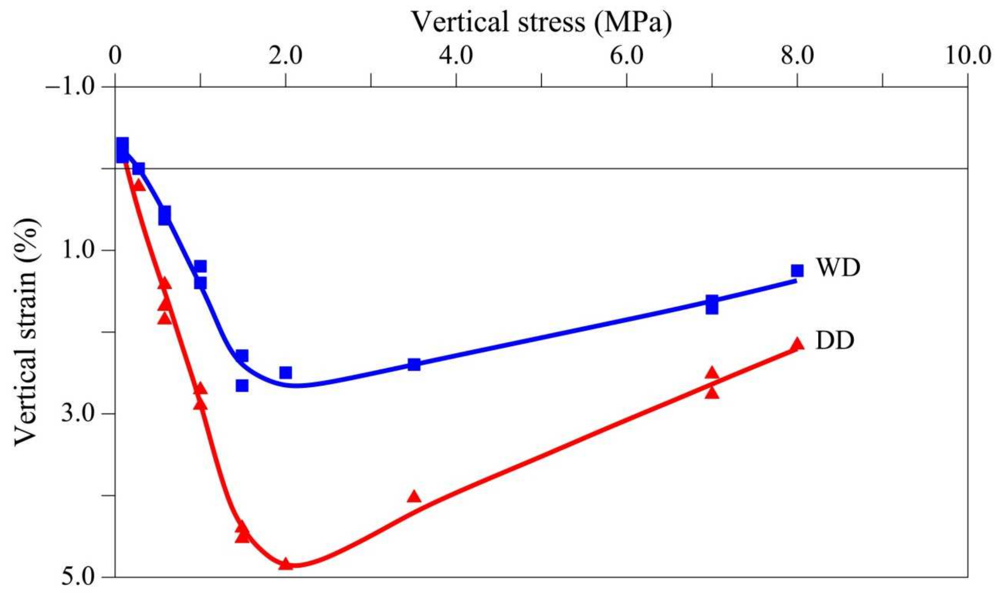



*Santucci de Magistris and Tatsuoka, 2004*

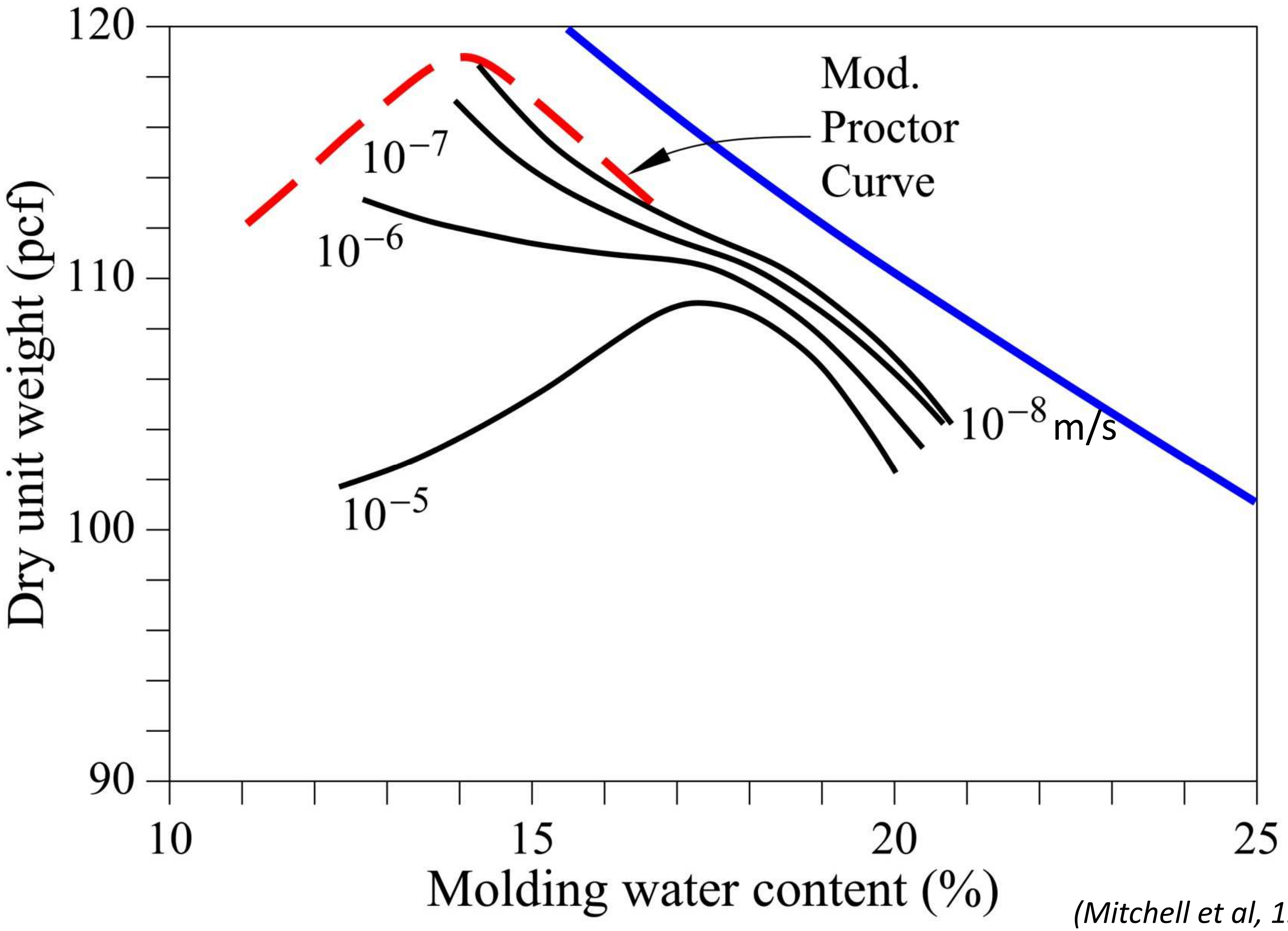
# Collapse behaviour of statically compacted low plasticity Barcelona silty clay




*(Suriol et al, 1998)*

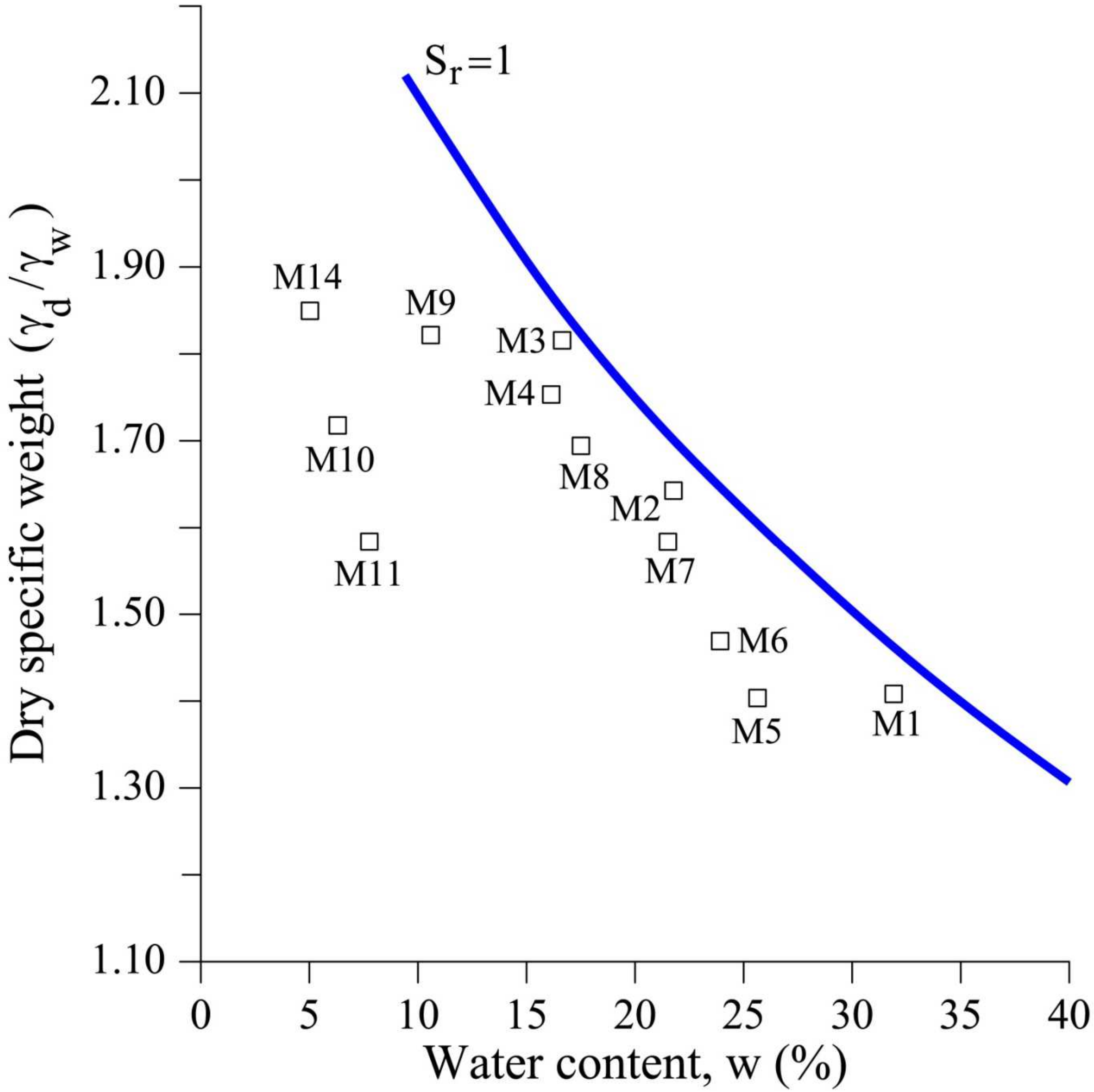
- Saturated Permeability




*(Mitchell et al, 1965)*

- Silty clay. Kneading compaction
- Strong microstructural effects. Permeability not explained by void ratio

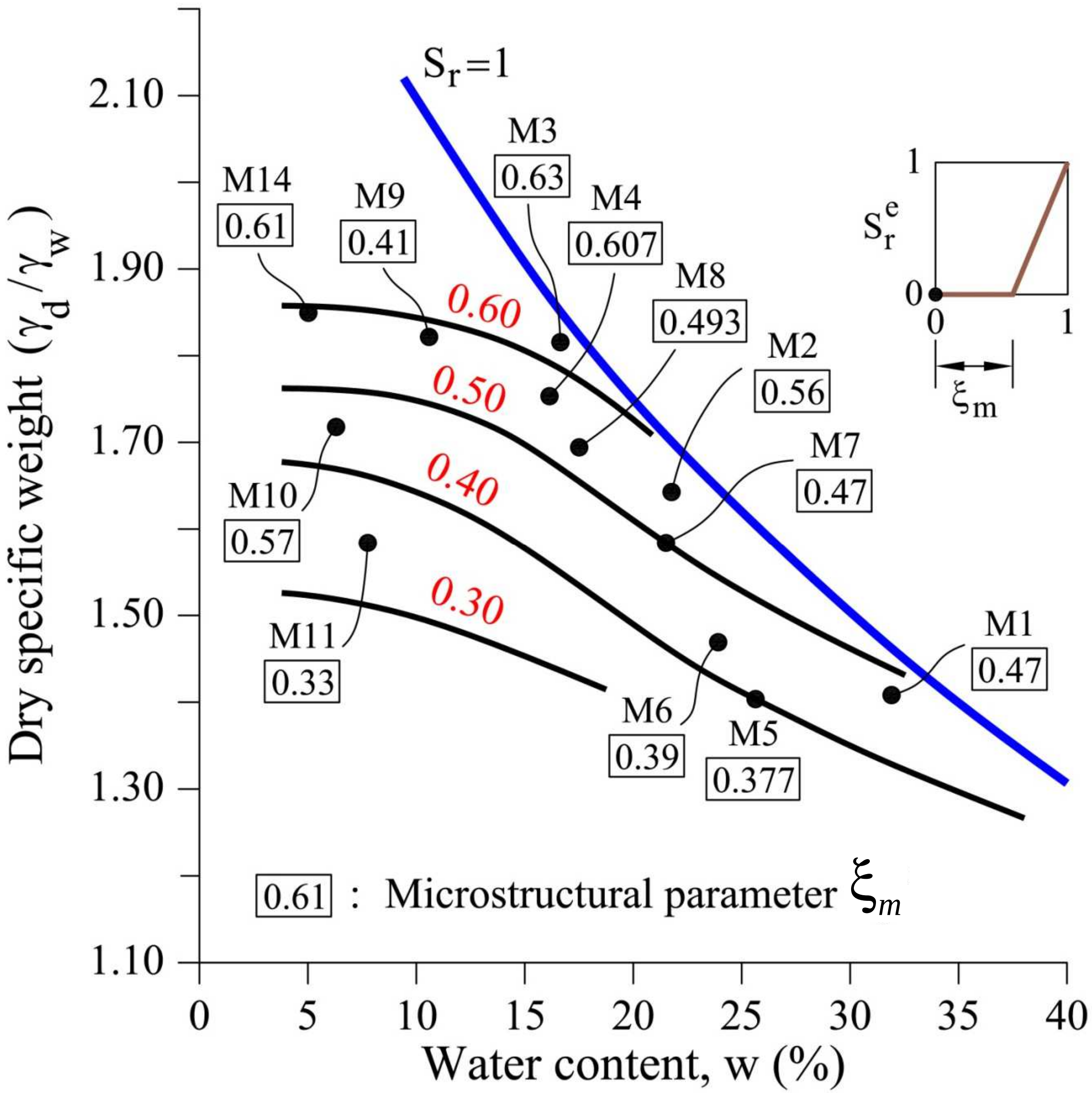
- Boom clay. As compacted conditions




*Merchán, 2011*

- A map of the microstructural parameter of Boom clay, statically compacted

$$\xi_m = \frac{e_m}{e}$$

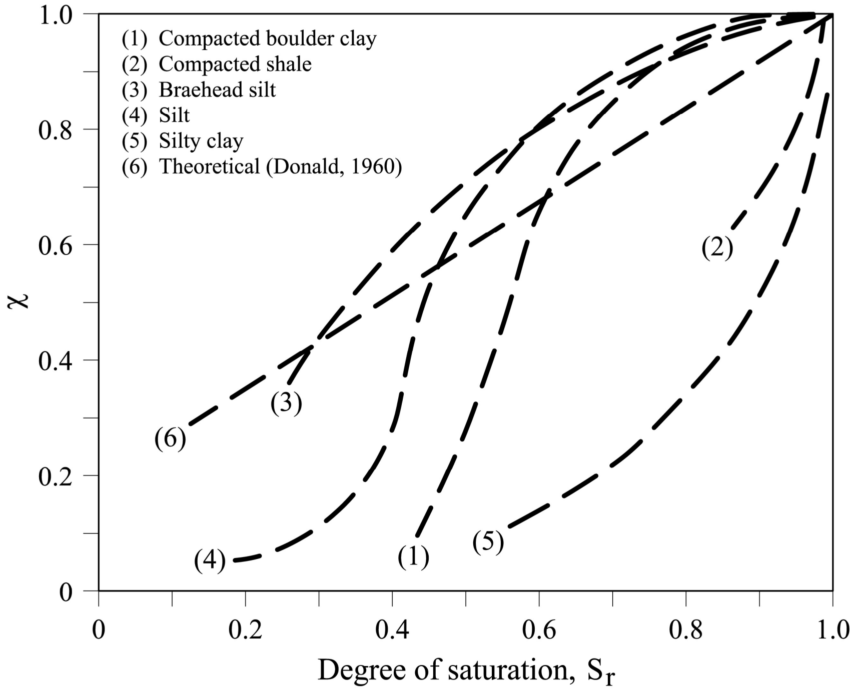



*(Based on data published by V. Merchán, 2011)*

- Effective stress fields and constitutive modelling

Bishop, 1959

$$\sigma' = \sigma - p_g + \chi s = \sigma_{net} + \chi s$$




(Hassanizadeh and Gray, 1980; Lewis and Schrefler, 1987; Hutter et al, 1999..)

$\chi : S_r$; fractional areas fluid-solid

## Common stress fields in constitutive modelling

a) Net stress + suction (Fredlund&Morgenstern, 1977)

- $\sigma' = \sigma - p_g = \sigma_{net}$
- $s = p_g - p_w$

b) "Intergranular stress"+ suction (Loret & Khalili, 2000; Jommi, 2000…)

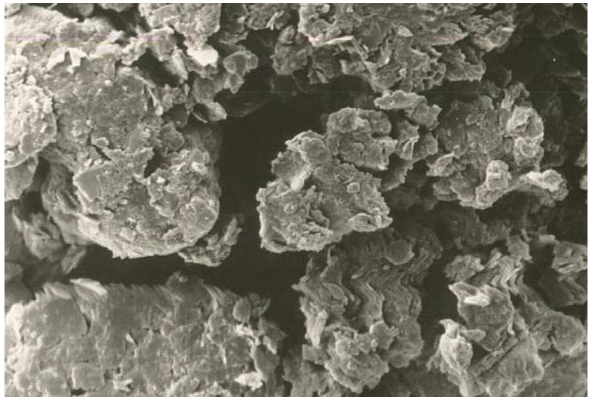
- $\sigma' = \sigma - p_g + S_r s = \sigma_{net} + S_r s$
- $s = p_g - p_w$

| | | |
|---|---|---|
| Work conjugates variables Houlsby, 1997 | $\sigma' = \sigma - p_g + \chi s = \bar{\sigma} + S_r s$ | and $\dot{\varepsilon}$ |
| | $n s$ | and $S_r$ |

# Attempts to include microstructure to predict strength and stiffness:

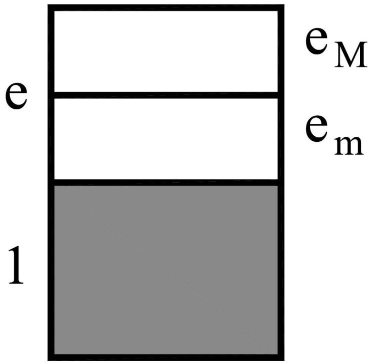
- Vanapalli et al, 1996
- Khalili and Khabbaz, 1998
- Romero and Vaunat, 2000
- Toll and Ong, 2003
- Tarantino and Tombolato, 2005
- Jotisankasa et al, 2009

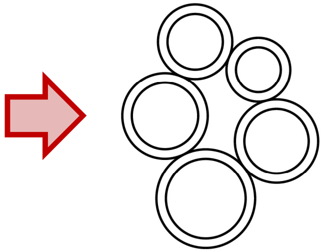
# The microstructural parameter



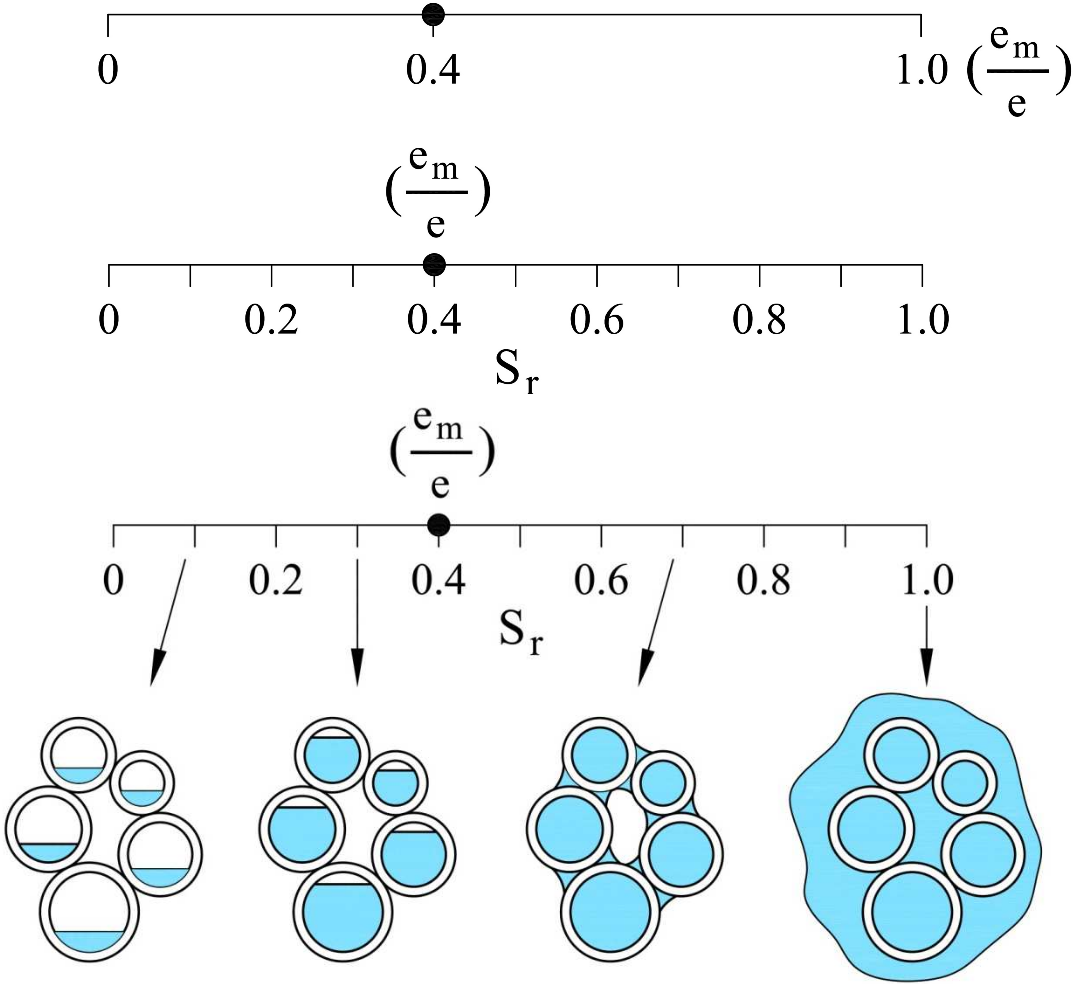
*Statically compacted Boom clay. Romero, 1998*

$\gamma_d$ = 13.7 KN/m$^3$; $w$ = 15%



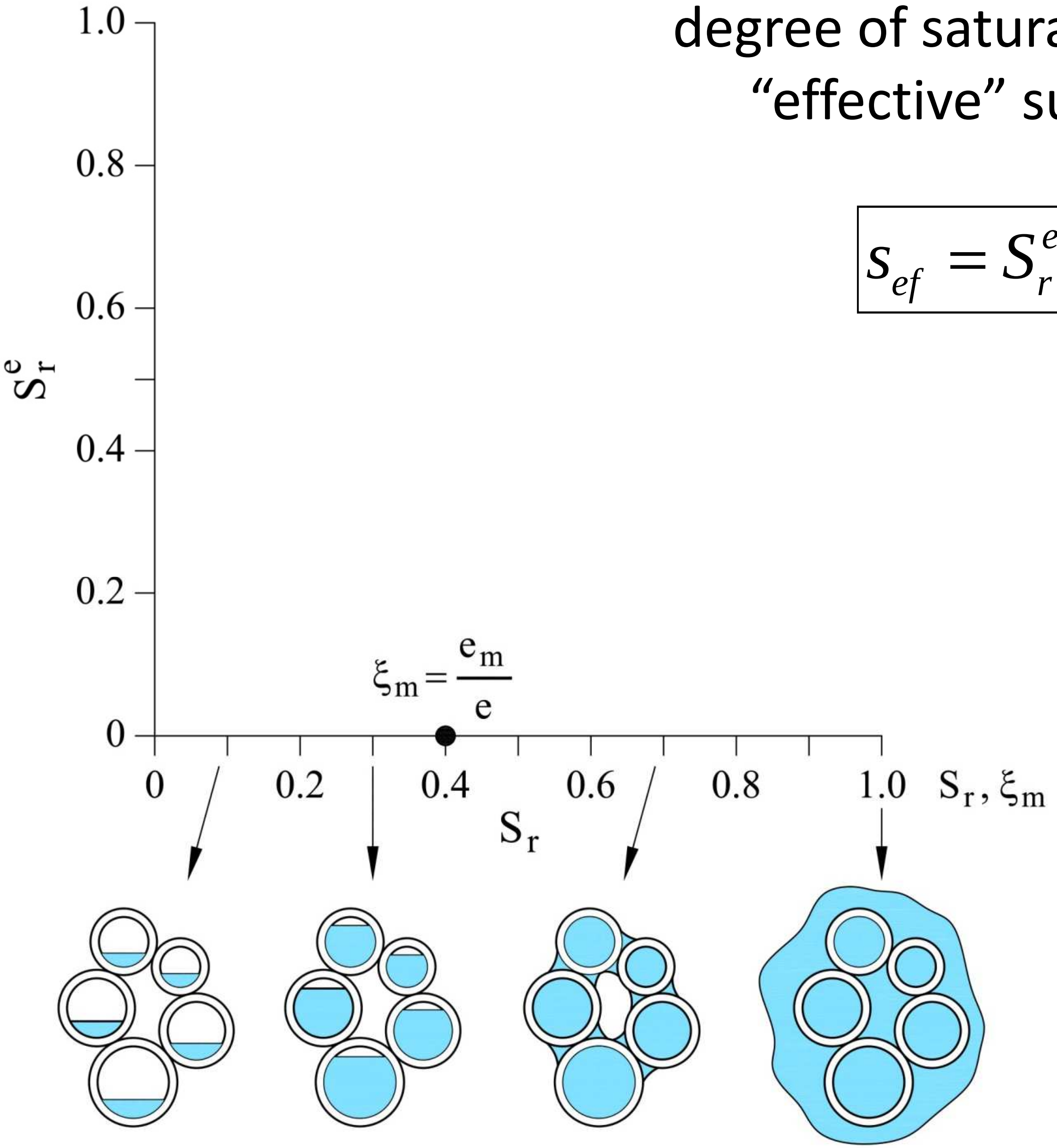



$$\frac{\text{Volume of micropores}}{\text{Total pore volume}} = \frac{e_m}{e} \quad (\equiv \xi_m)$$

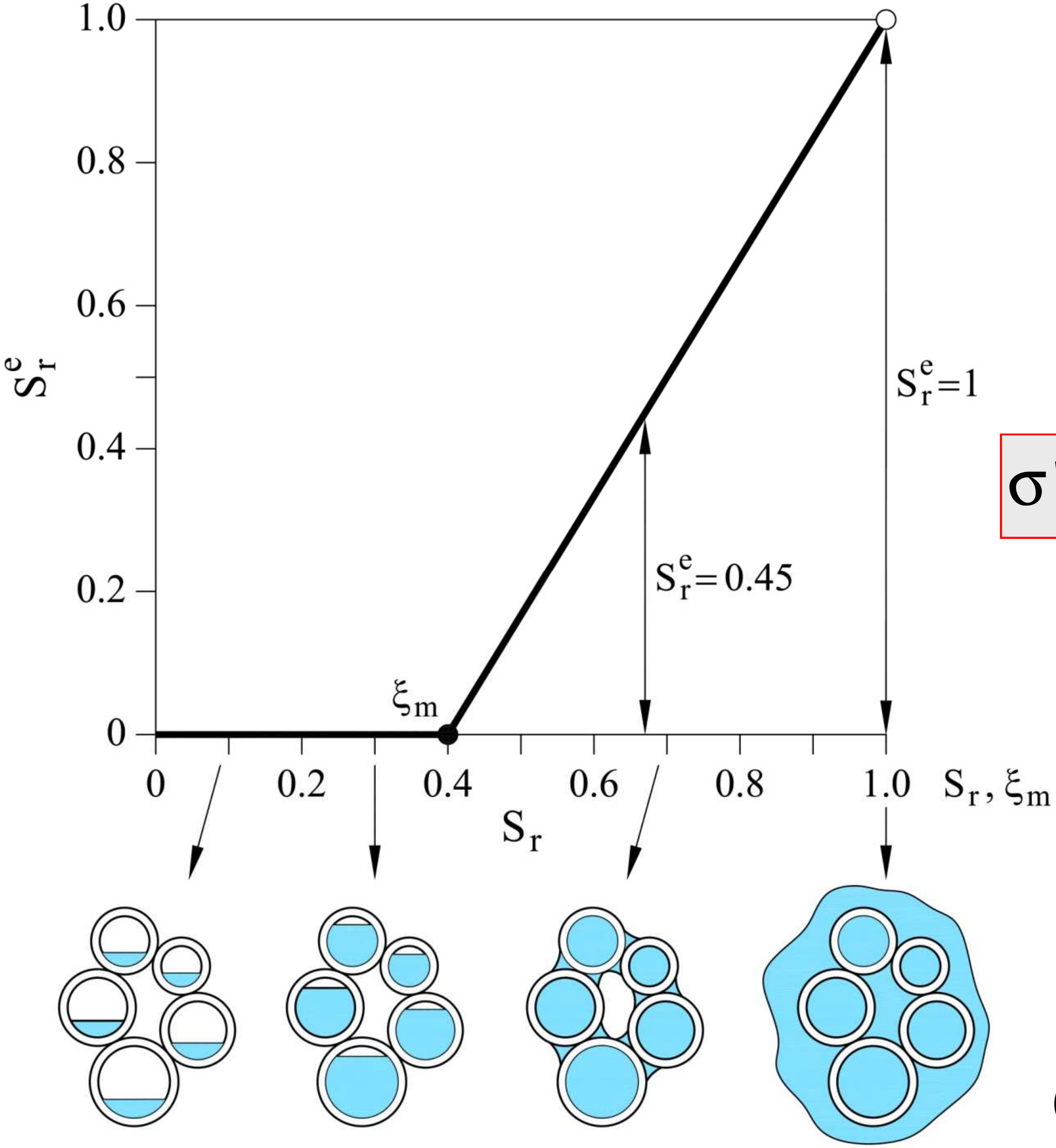


- Microstructural parameter, degree of saturation and "effective" suction

$$s_{ef} = S_r^e s$$



## Effective degree of saturation and effective stress




$$\sigma' = \sigma - p_g + S_r^e s$$

$$S_r^e = \left\langle \frac{S_r - \xi_m}{1 - \xi_m} \right\rangle \qquad \langle \bullet \rangle = 0.5(\bullet + |\bullet|)$$

$$\sigma' = \sigma - p_g + S_r^e(S_r, e_m, e)s$$

Effective degree of saturation

+

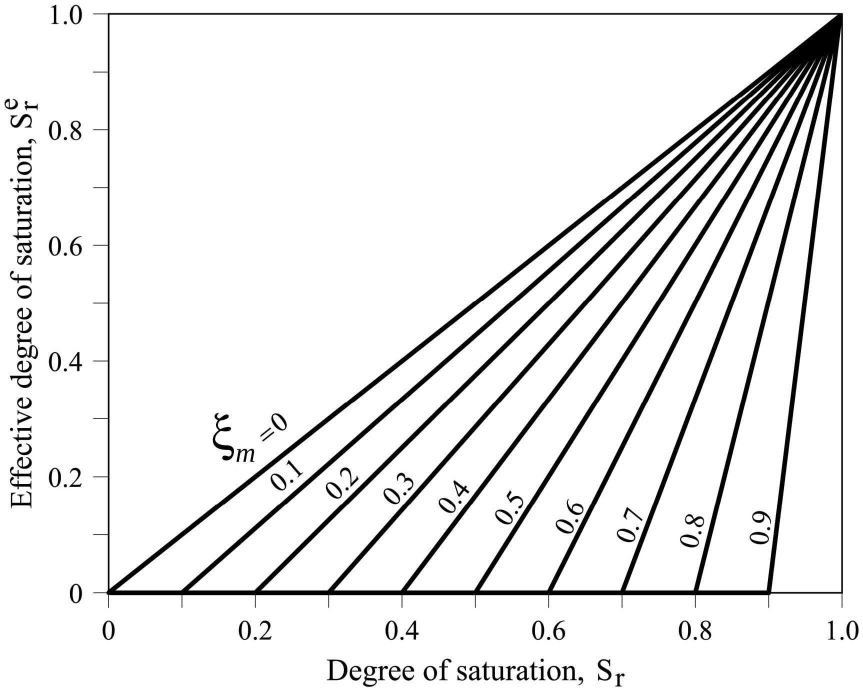
$$s \text{ or } s_{ef}$$

*(Alonso, Pereira, Vaunat, Olivella, 2010)*

## The effective degree of saturation

### Discontinuous

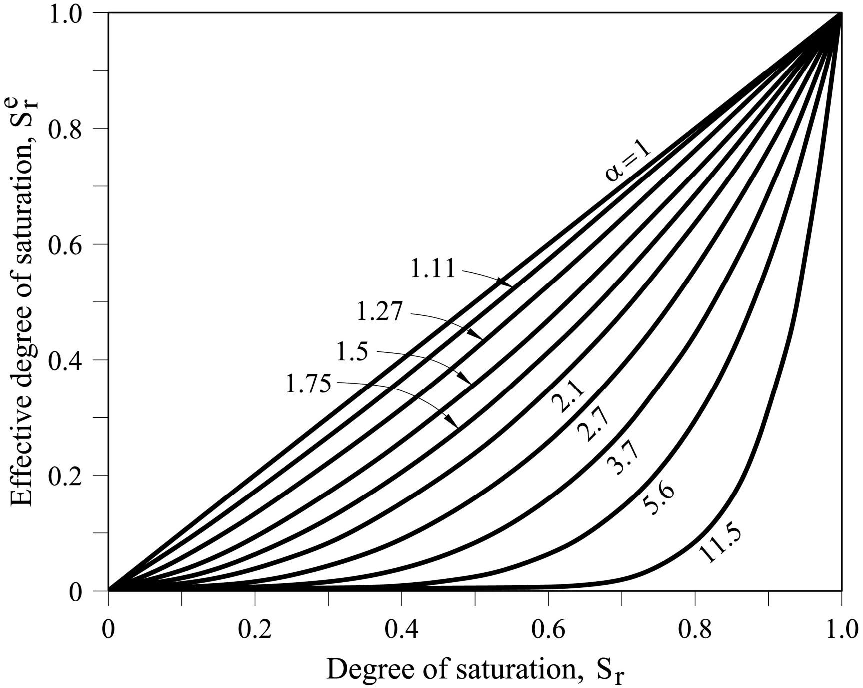
$$S_r^e = \left\langle \frac{S_r - \xi_m}{1 - \xi_m} \right\rangle$$




### Potential function

$$\chi = (S_r)^{\alpha}$$

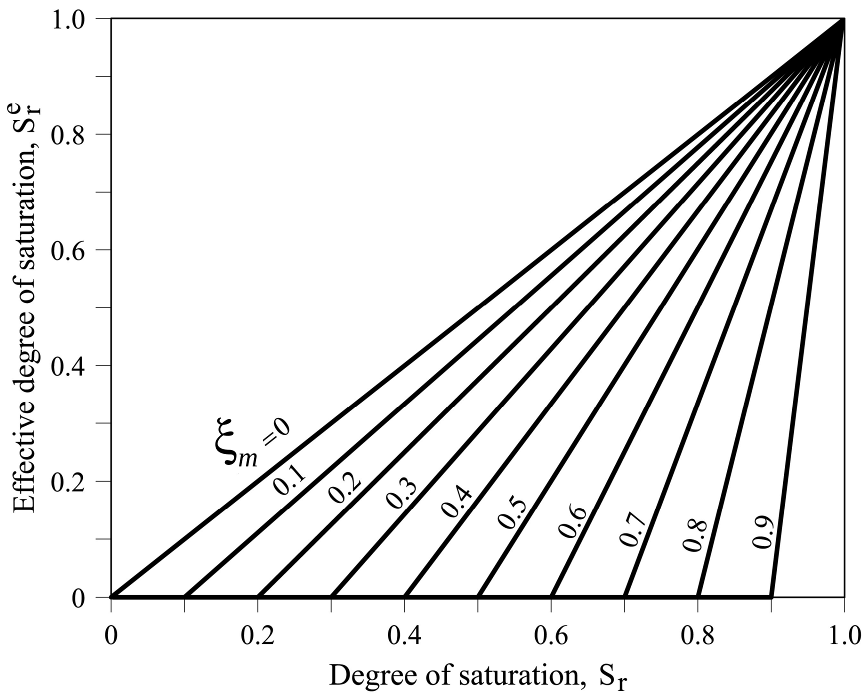
$$\alpha = \alpha(\xi_m)$$



## The effective degree of saturation

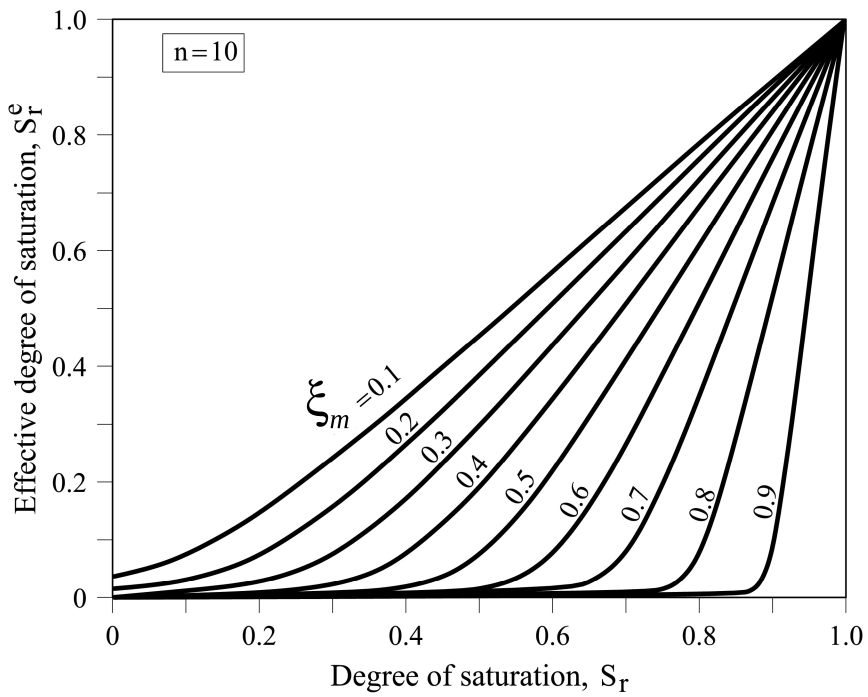
### Discontinuous

$$S_r^e = \left\langle \frac{S_r - \xi_m}{1 - \xi_m} \right\rangle$$



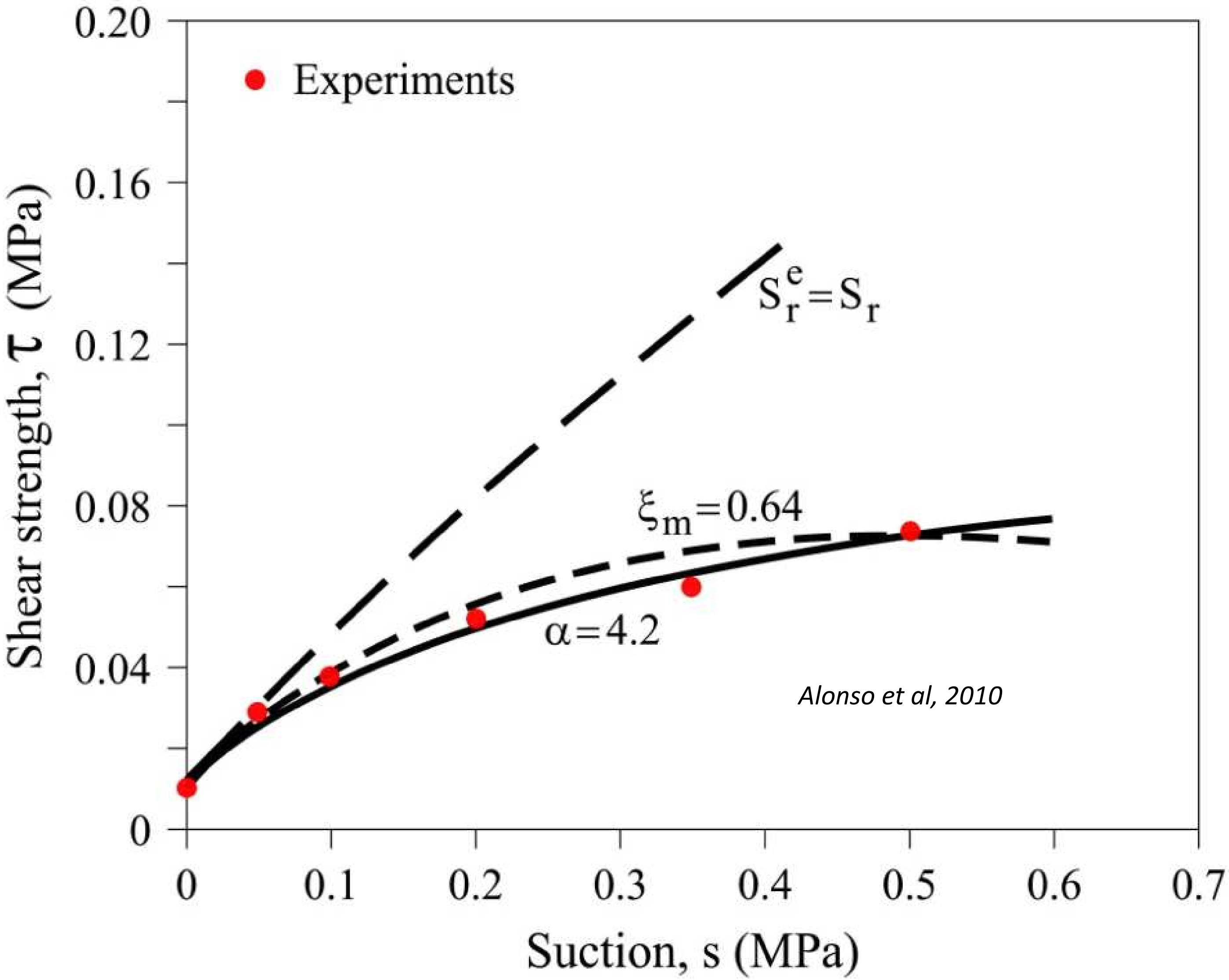

### Smoothing function

$$S_r^e = \frac{S_r - \xi_m}{1 - \xi_m} + \frac{1}{n_{smooth}} \ln\left[1 + \exp\left(-n_{smooth}\frac{S_r - \xi_m}{1 - \xi_m}\right)\right]$$



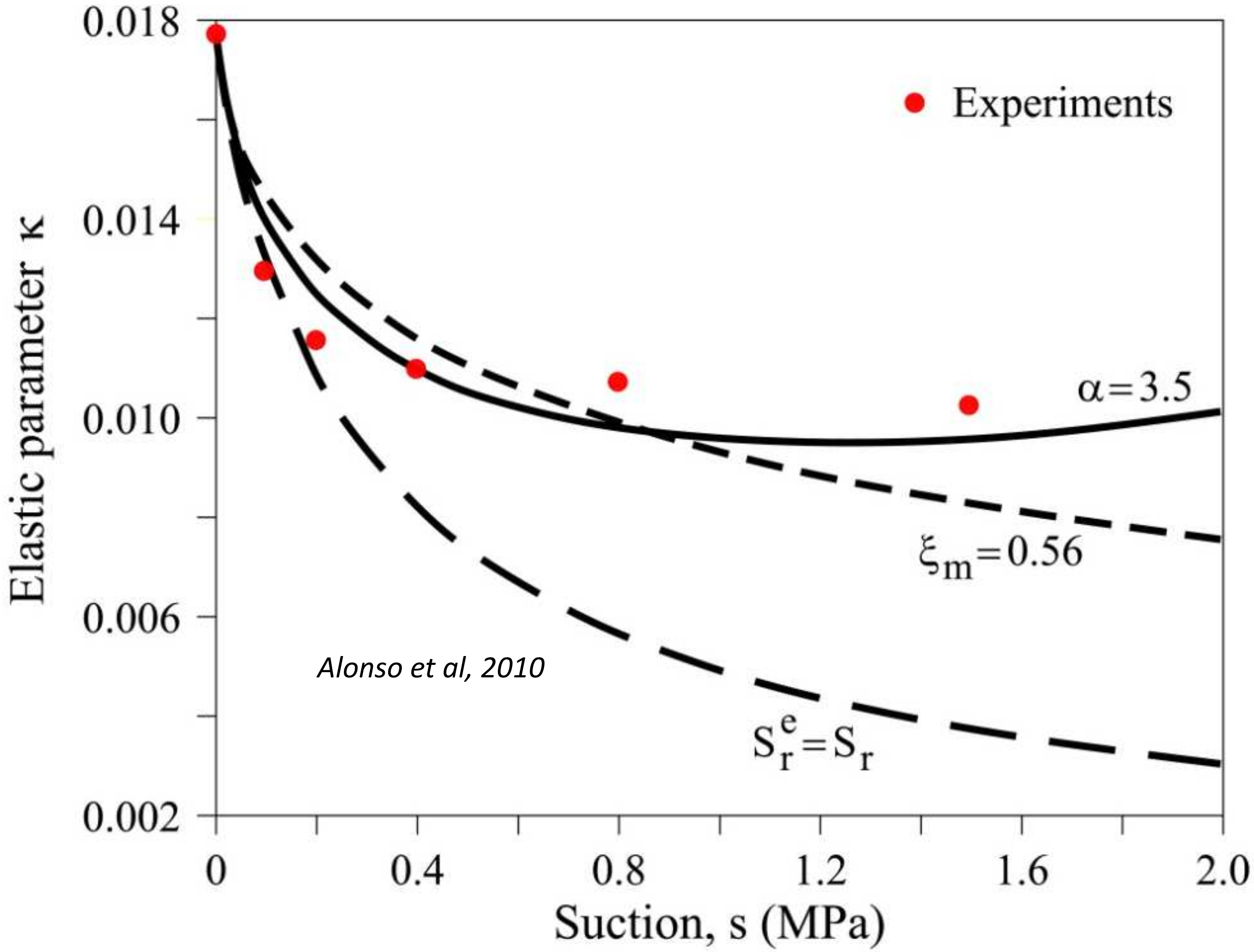

*Gesto et al, 2011*

# Strength: Tests on Canadian glacial till, $w_l$ = 35.5%; $w_p$ = 16.8% *(Vanapalli et al., 1996)*




*Alonso et al, 2010*

# Stiffness: Low plasticity Jossigny silt. Oedometer tests



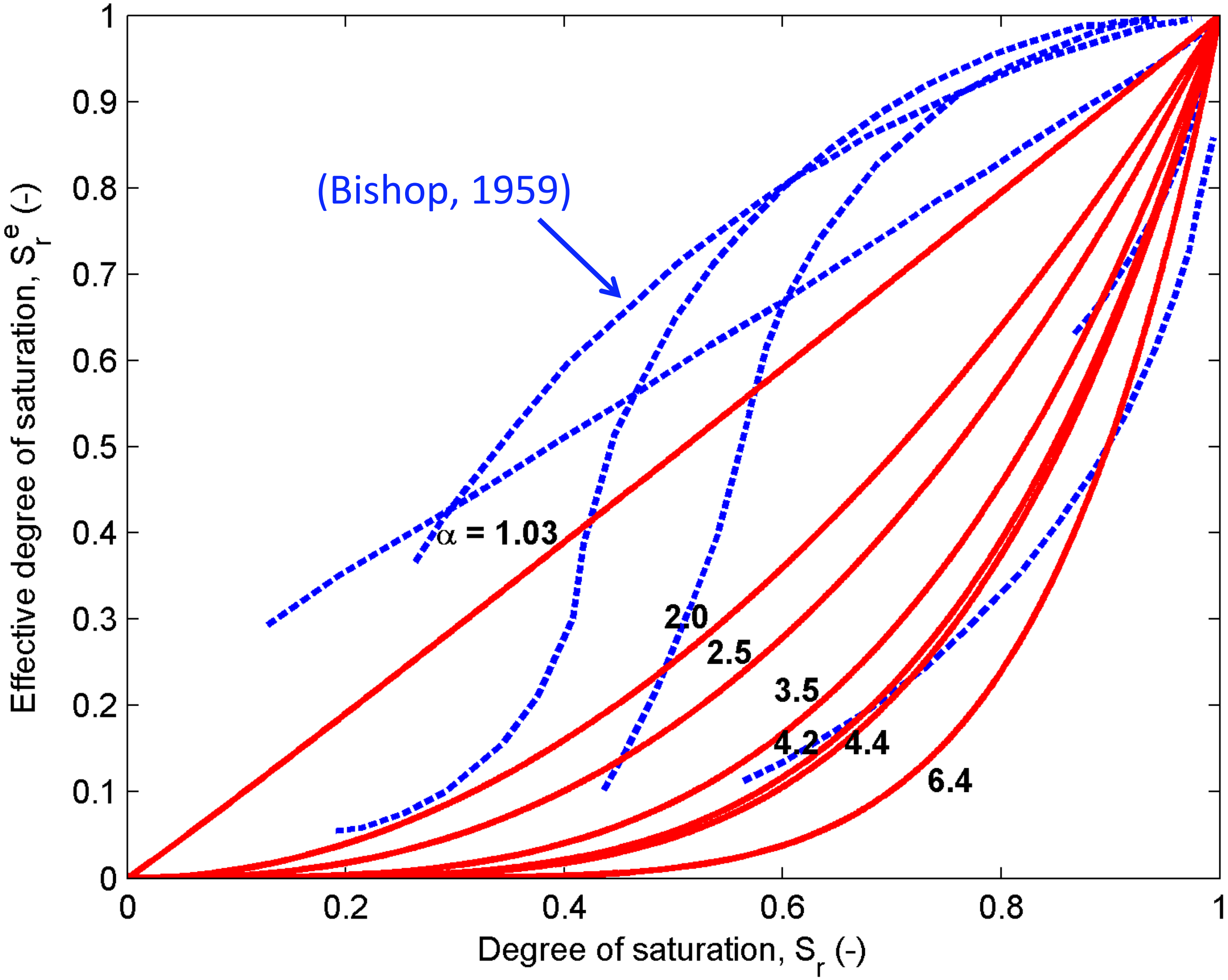

*(Test results reported by Vicol, 1990)*

Microstructural Parameter of different soils.
Identified by indirect tests (stiffness, strength)

| Soil | $\xi_m$ (-) | $\alpha$ | Plasticity |
|---|---|---|---|
| Decomposed tuff, Fredlund *et al.* (1996) | **0.02** | **1.03** | Non plastic |
| Vallfornés dam core, Alonso (1998) | **0.25** | **2.0** | Non plastic |
| Sion silt, Geiser *et al.* (2006) | **0.4** | **2.5** | IP = 8.7% |
| Jossigny silt, Vicol (1990) | **0.56** | **3.5** | 18% |
| Glacial till, Vanapalli *et al.* (1996) | **0.64** | **4.2** | 18.7% |
| Boom clay ($\gamma_d$=13.7 kN/m$^3$), Romero (1999) | **0.42** | **4.4** | 28.8% |
| Boom clay ($\gamma_d$=16.7 kN/m$^3$), Romero (1999) | **0.63** | **6.4** | 28.8% |

*(Alonso et al, 2010)*

- Bishop's effective stress parameter and the effective degree of saturation
(α values in red curves)



Let us define unsaturated soil behaviour in terms of two independent stress fields:

- Constitutive stress: $\bar{\sigma} = \sigma - p_g + \bar{S}_r s$
- Effective suction: $\bar{s} = \bar{S}_r s$

$$\bar{S}_r = \frac{S_r - \xi_m}{1-\xi_m} + \frac{1}{n_{smooth}} \ln\left[1 + \exp\left(-n_{smooth} \frac{S_r - \xi_m}{1-\xi_m}\right)\right]$$

$$S_r^e = \bar{S}_r$$

$$s_{ef} = \bar{s}$$

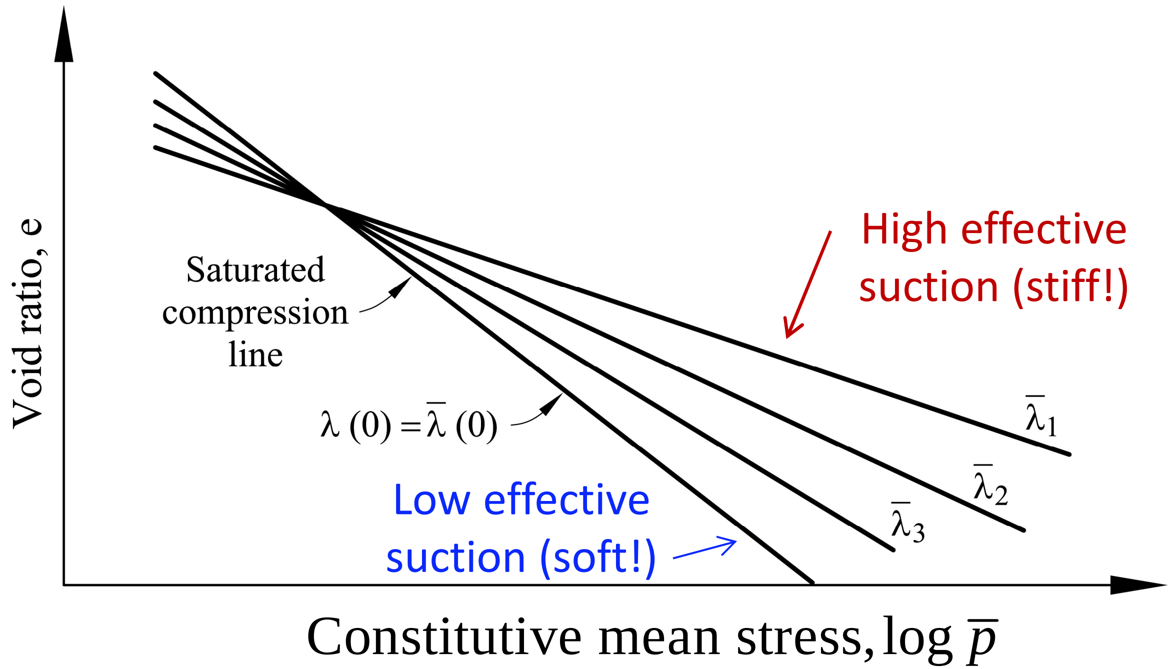
Change of notation!

*(Alonso, Pinyol, Gens, 2010)*

## ▪ Isotropic stress states

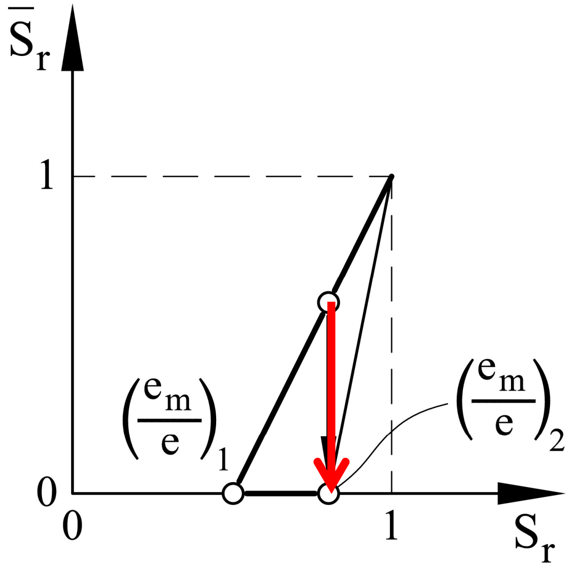
• Compressibility: Elastic: $de^e = -\bar{\kappa}\dfrac{d\bar{p}}{\bar{p}}$

Elastoplastic: $de^{ep} = -\bar{\lambda}\dfrac{d\bar{p}}{\bar{p}}\bigg|_{\bar{s}=\text{constant}}$ $\qquad \dfrac{\bar{\lambda}(\bar{s})}{\lambda(0)} = f(\bar{s}) = f(\bar{S}_r s)$

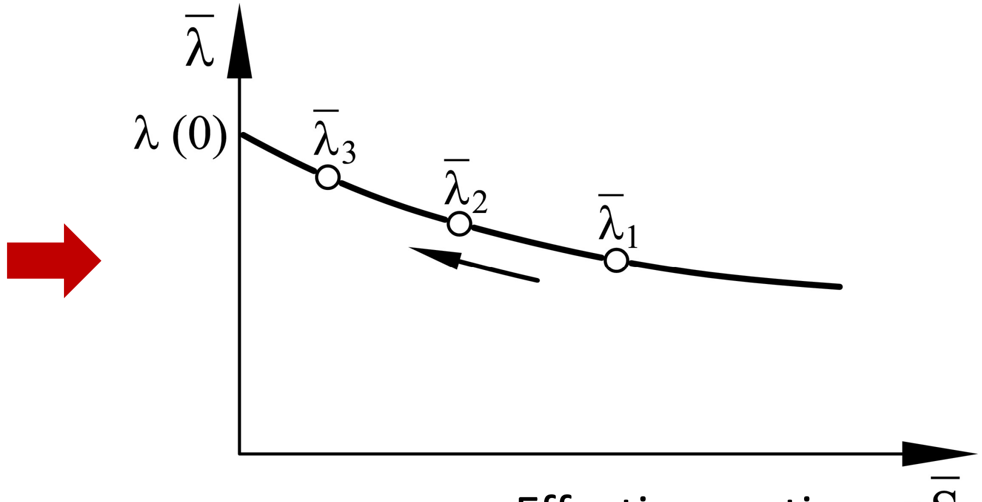



Definition of compression lines in terms of effective stress $\log \bar{p} = \log\left(p_{net} + \bar{S}_r s\right)$

Suction controlled tests do not provide $\bar{\lambda}$ , even if the microstructural void ratio is known and assumed to be constant, because void ratio is changing during loading and effective suction is thereby varying continuously!



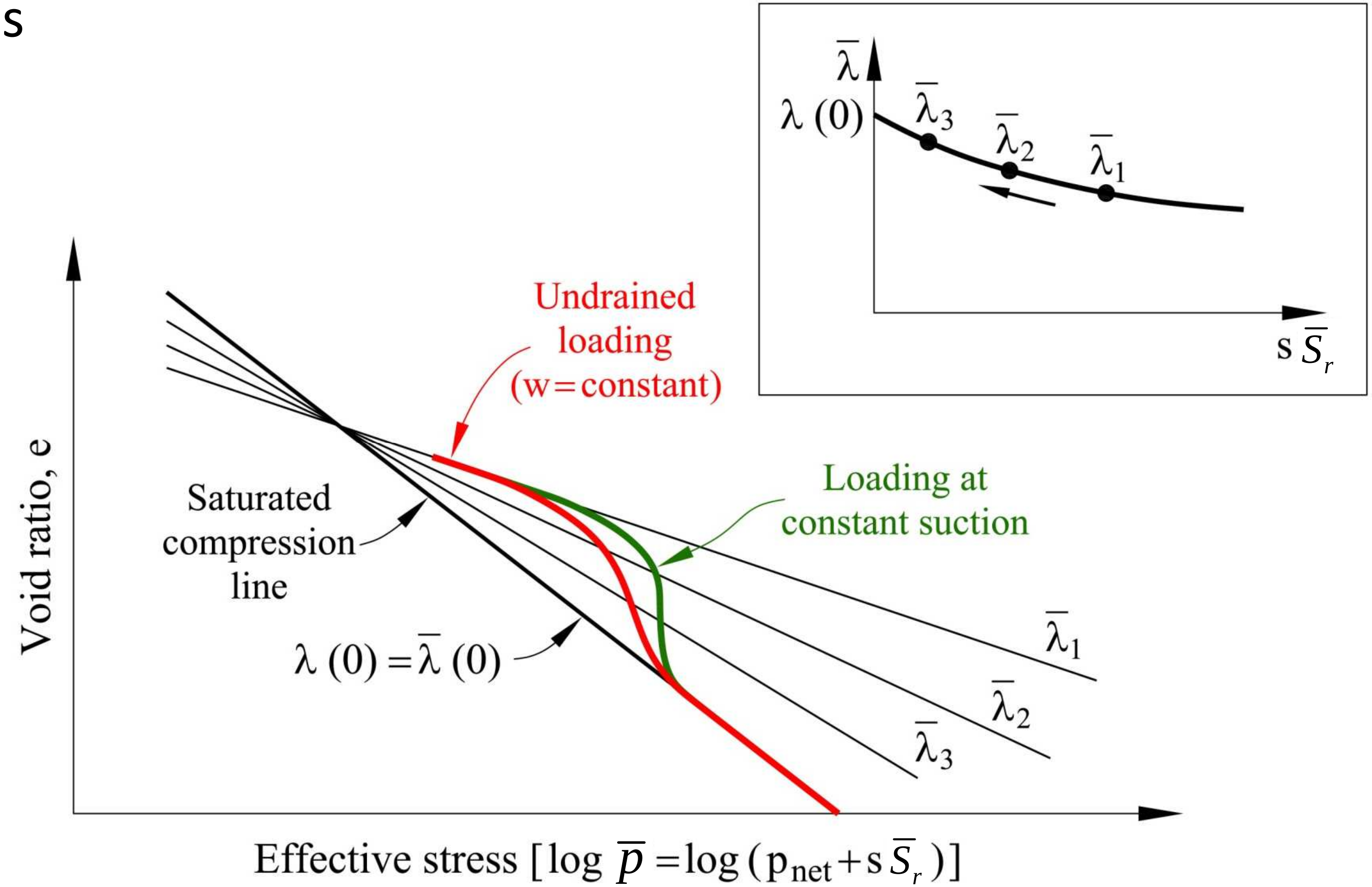

Effect of increasing void ratio on effective degree of saturation for a constant degree of saturation: Effective suction decreases




Effect of decreasing effective suction (volumetric compression) on compressibility coefficient

# Compression lines

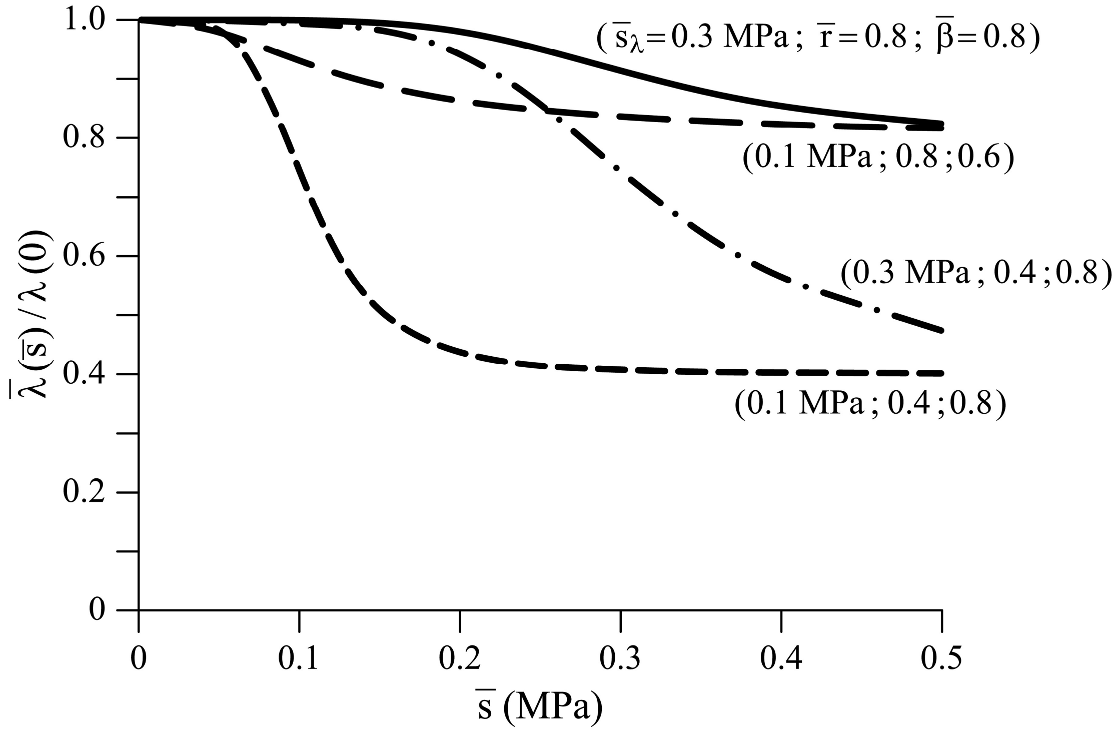
- Compressibility decreases with effective suction
- Effective suction decreases during loading because void ratio reduces



$$\frac{\bar{\lambda}(\bar{s})}{\lambda(0)} = f(\bar{s}) = f(\bar{S}_r s) \ ?$$

$$\frac{\bar{\lambda}(\bar{s})}{\lambda(0)} = \bar{r} + (1-\bar{r})\left[1-\left(\frac{\bar{s}}{\bar{s}_\lambda}\right)^{1/(1-\bar{\beta})}\right]^{-\bar{\beta}}$$

(Unique expression for the entire compaction plane)

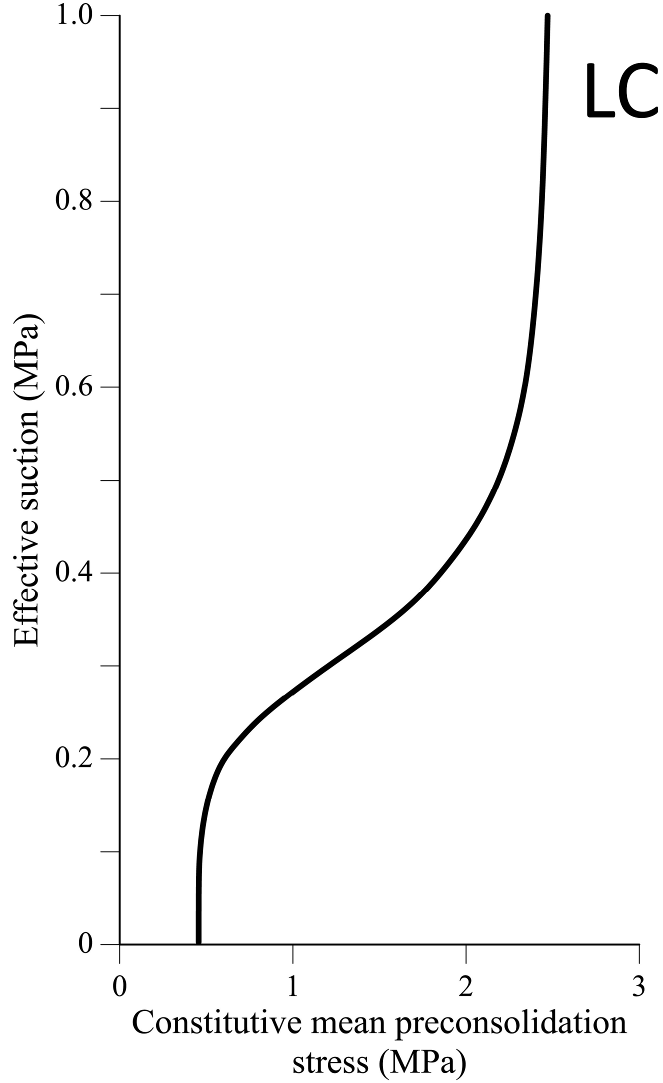



$\bar{s}_\lambda$ ?

The air entry value

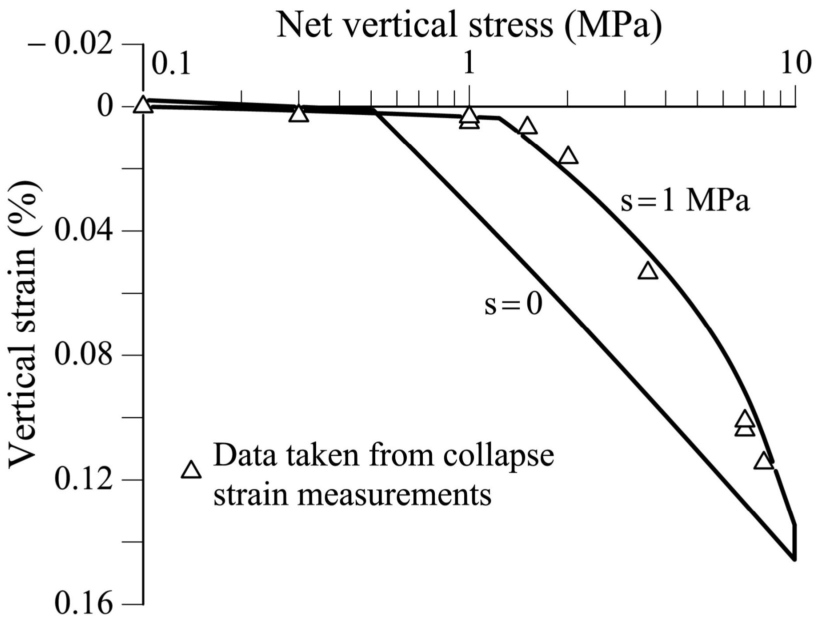
Variation of isotropic compressibility with effective suction for different parameter values

Yielding for isotropic states (LC): $$\frac{\bar{p}_0}{\bar{p}_c} = \left( \frac{p_0^*}{\bar{p}_c} \right)^{\frac{\lambda(0)-\kappa}{\bar{\lambda}(\bar{s})-\kappa}}$$

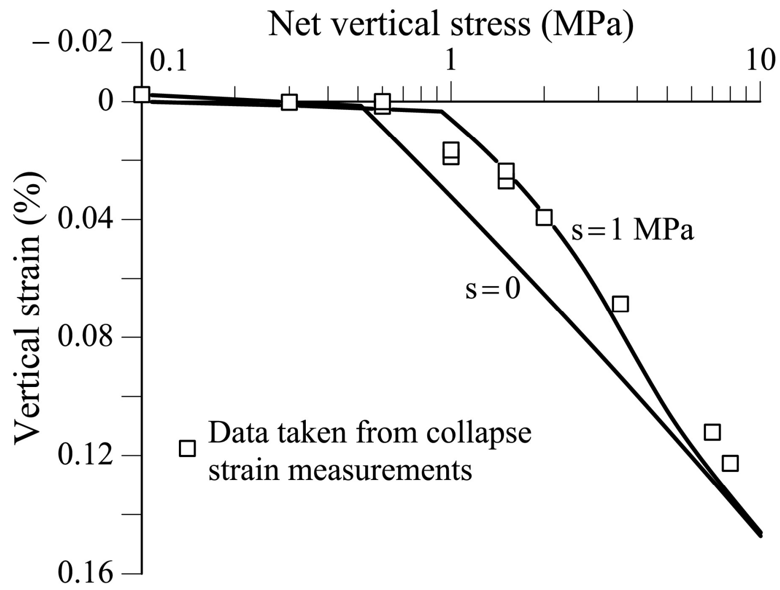


# Estimated experimental compression curves of compacted Barcelona silty clay in the range 0-8 MPa of vertical stress and model predictions

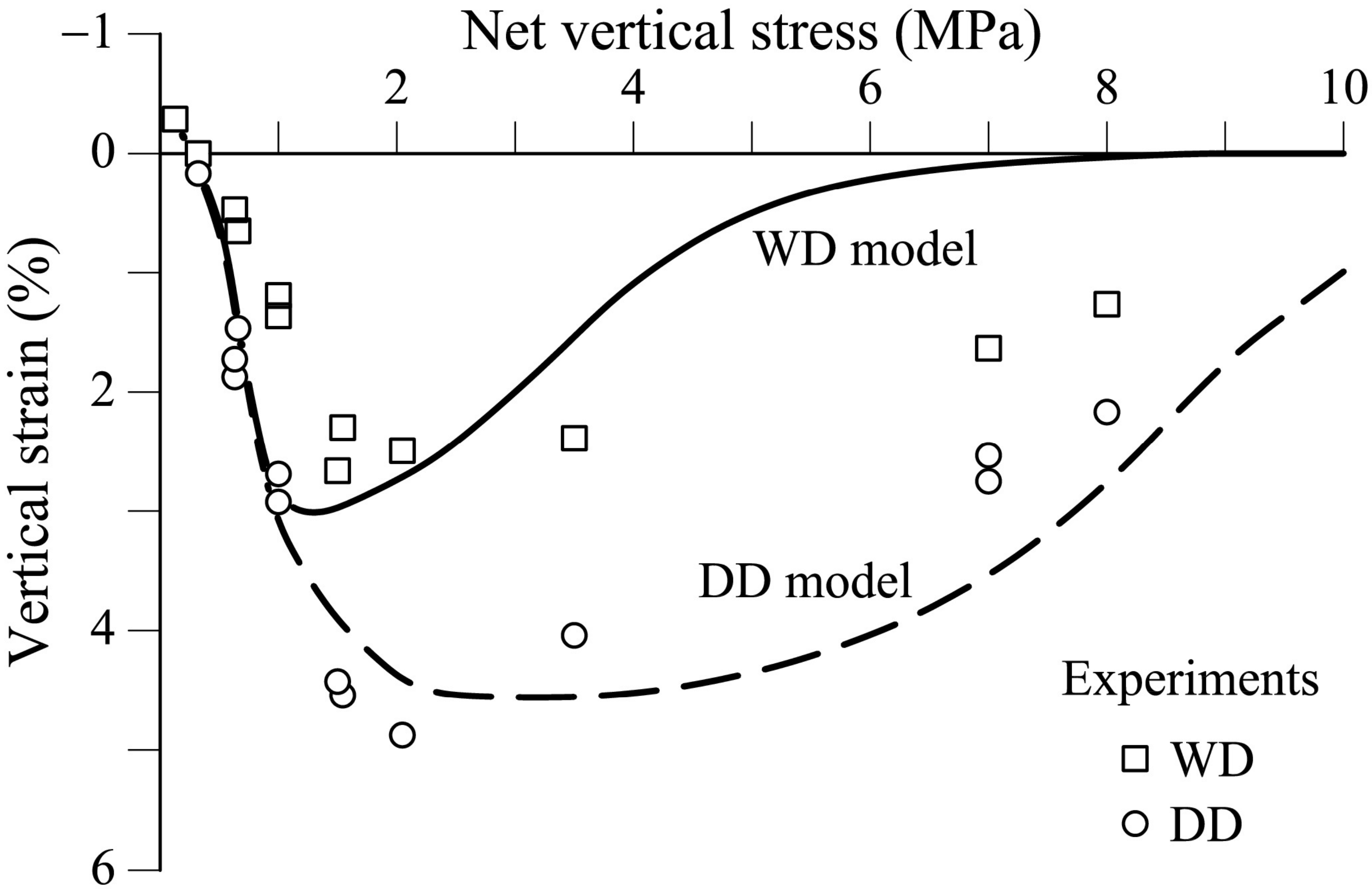
## DD samples




## WD samples

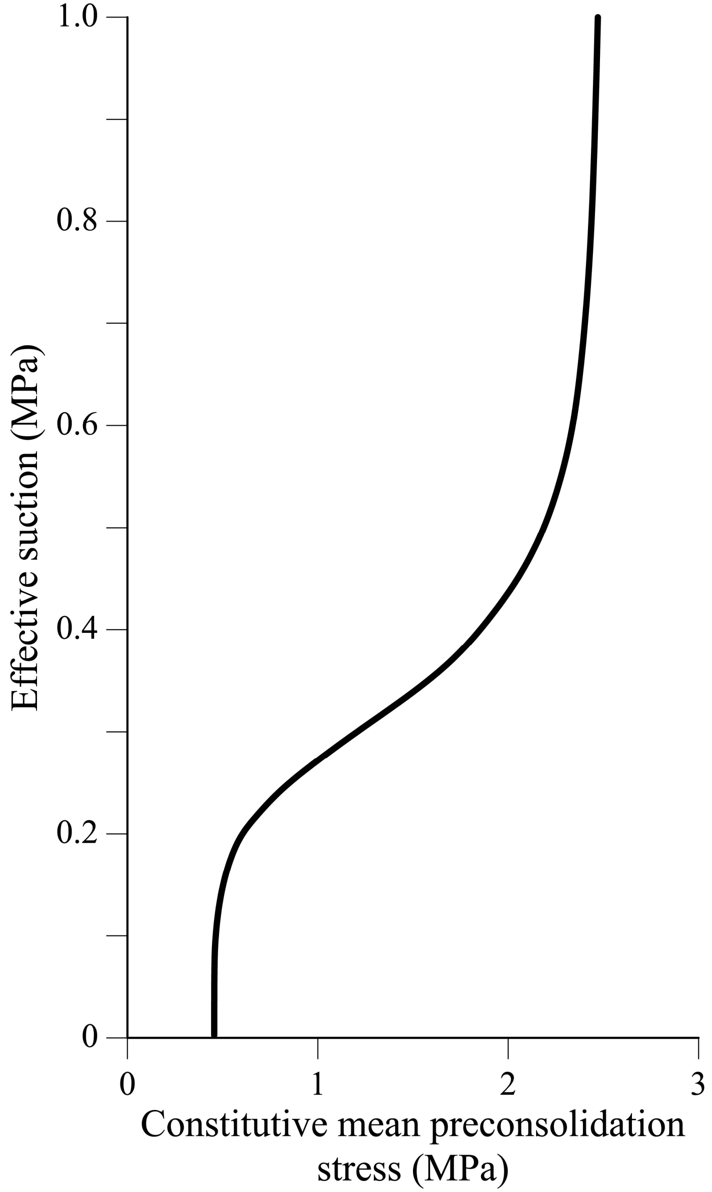


# Measured and calculated collapse strains of samples DD and WD

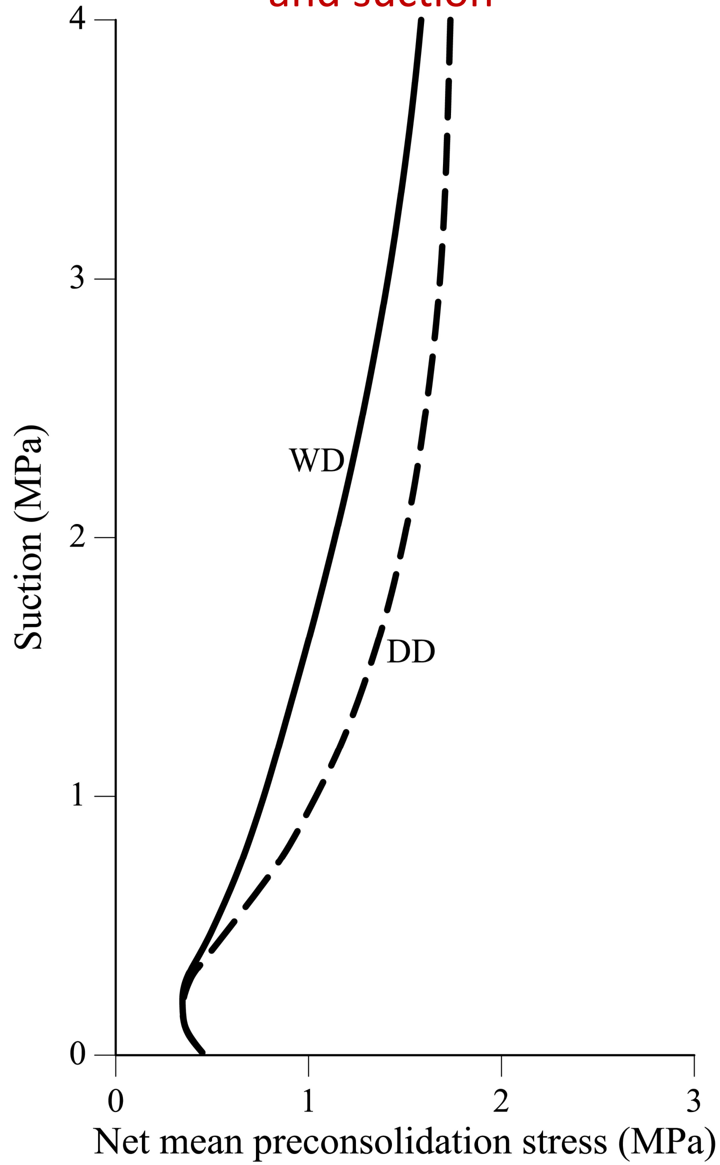


# Initial LC yield curves of samples DD and WD

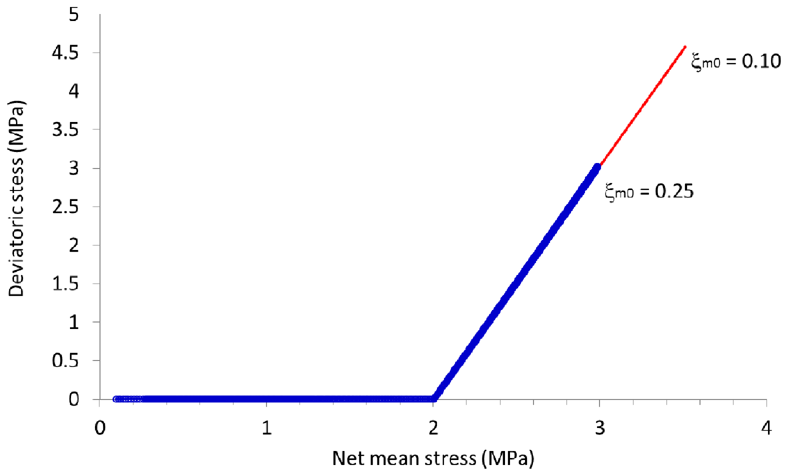
In terms of constitutive stress and effective suction

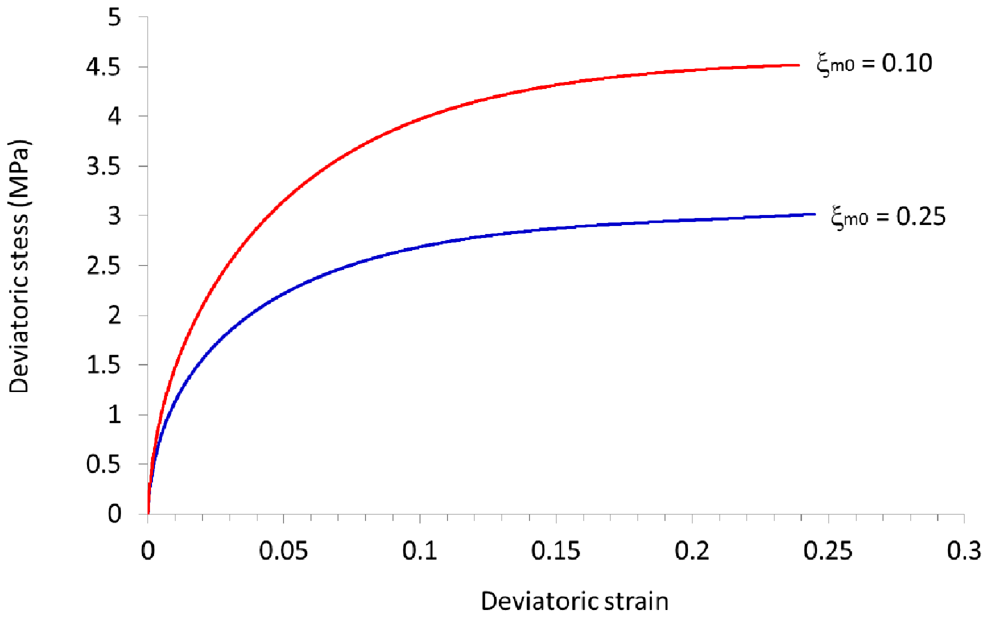


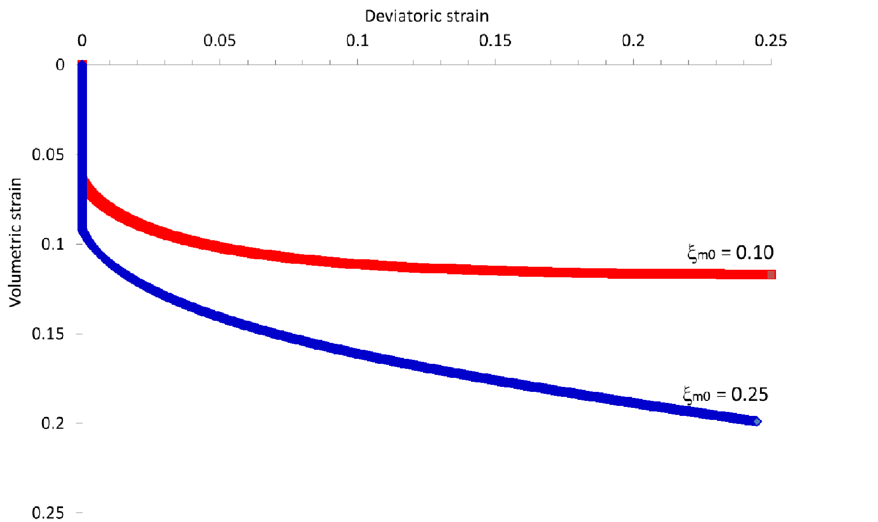

In terms of net stress and suction



- Simulated triaxial test. Dry and wet of optimum

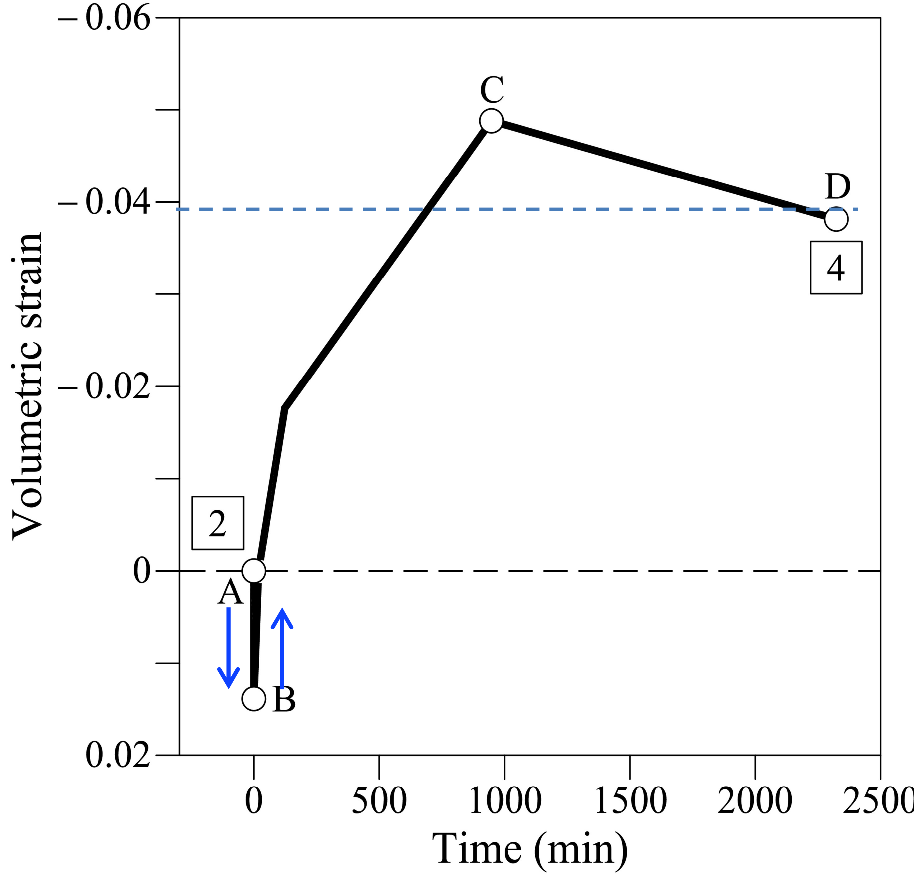


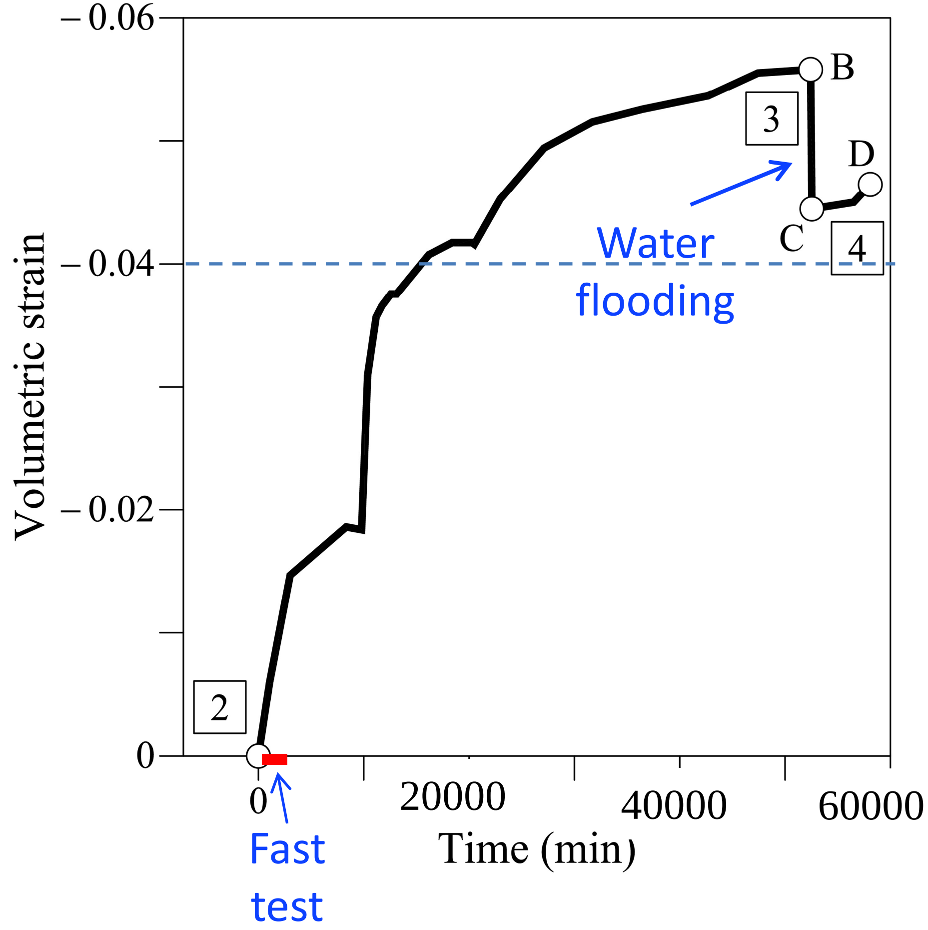



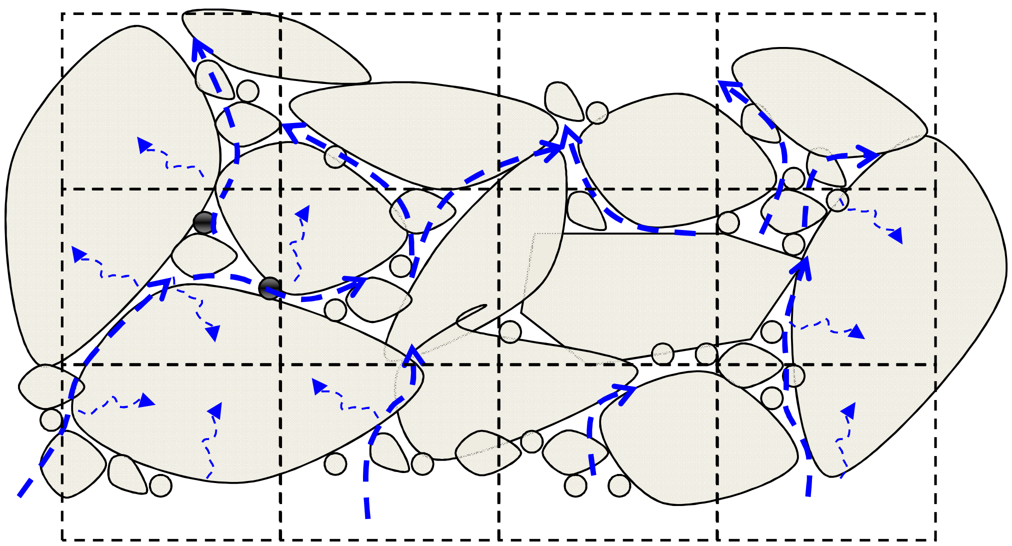
## ➢ Local equilibrium of suction

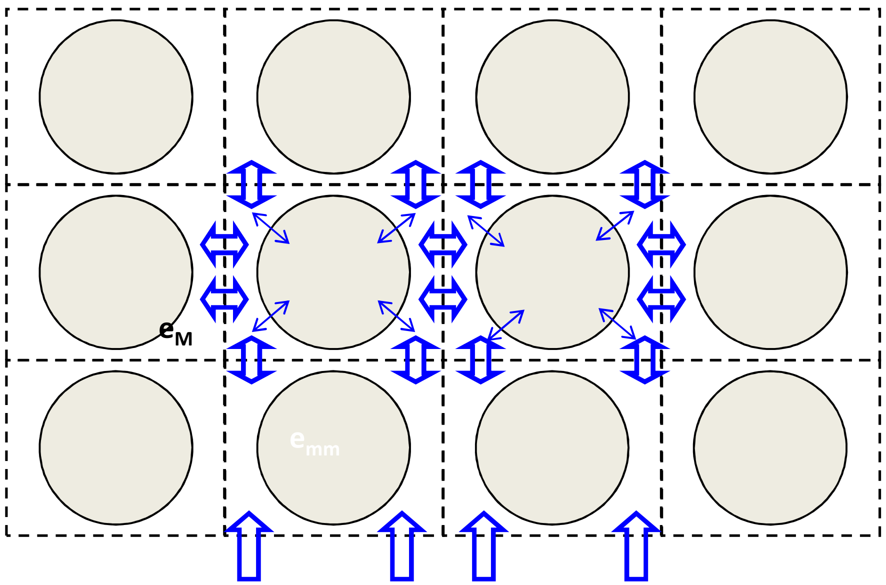
FAST WETTING

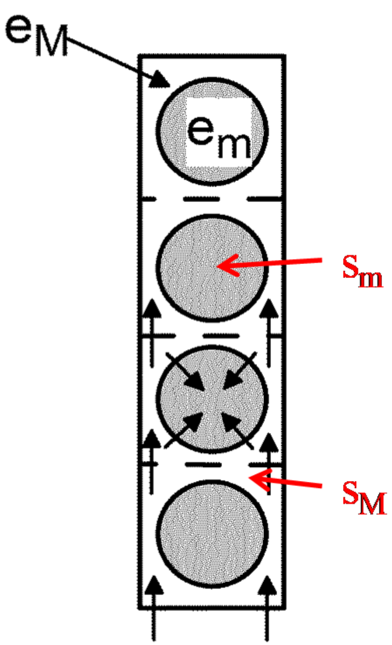



SLOW WETTING

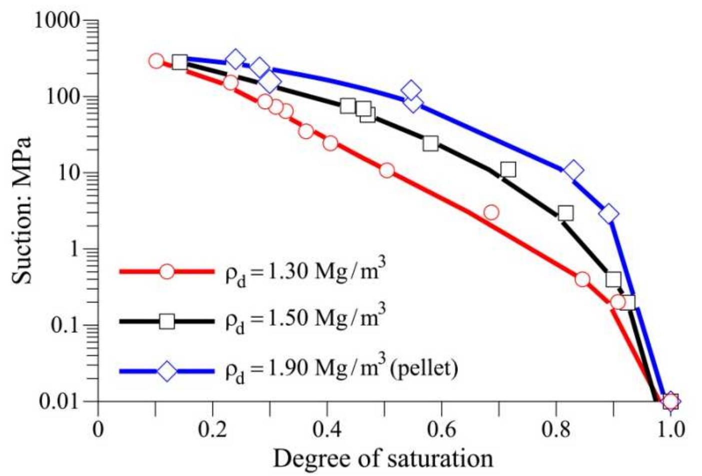





e_M
e_mm

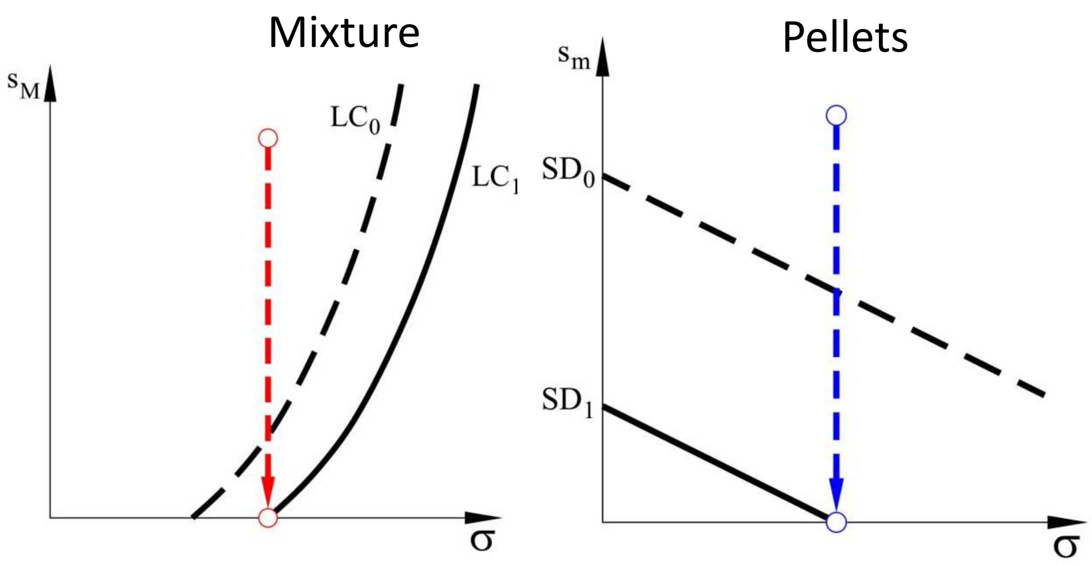



- Micro enclosed by Macropores
- Flow through Macropores → $\frac{\partial}{\partial t}(n_M S_{rM}) - \nabla \cdot (k_M \nabla \varphi_M) = f^w_{M\to m}$
- Micro/aggregates: N BVP's
  - Boundary condition: $s_M$
  - Water mass balance: → $\frac{\partial}{\partial t}(n_m S_{rm}) - \nabla \cdot (k_m \nabla \varphi_m) = 0$
- Flow through Macropores: $k_M = k_{iM}(e_M) k_{rM}(S_{rM})$
- Flow through micropores $k_m = k_{im}(e_m) k_{rm}(S_{rm})$
- Wetting WR branches:



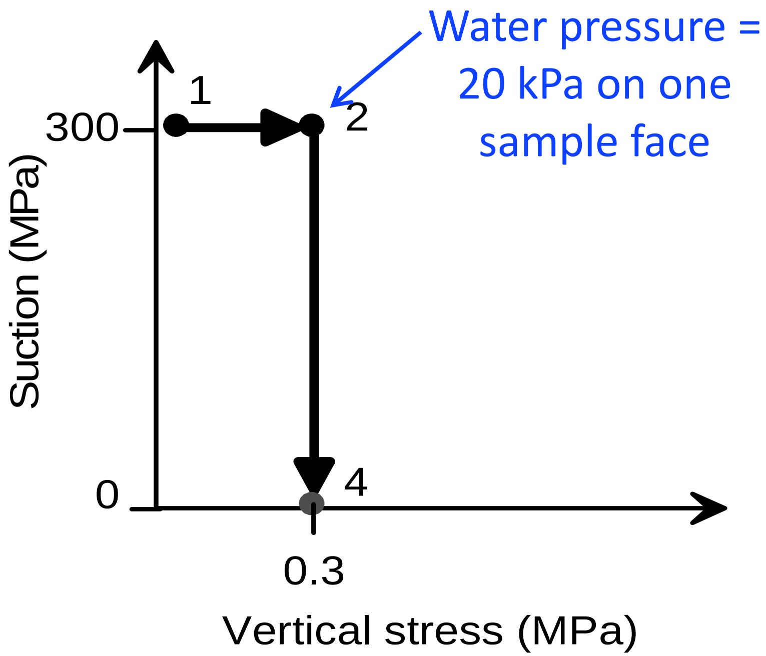

*(Alonso, Romero, Hoffmann, 2012)*

- Elastoplastic behaviour:

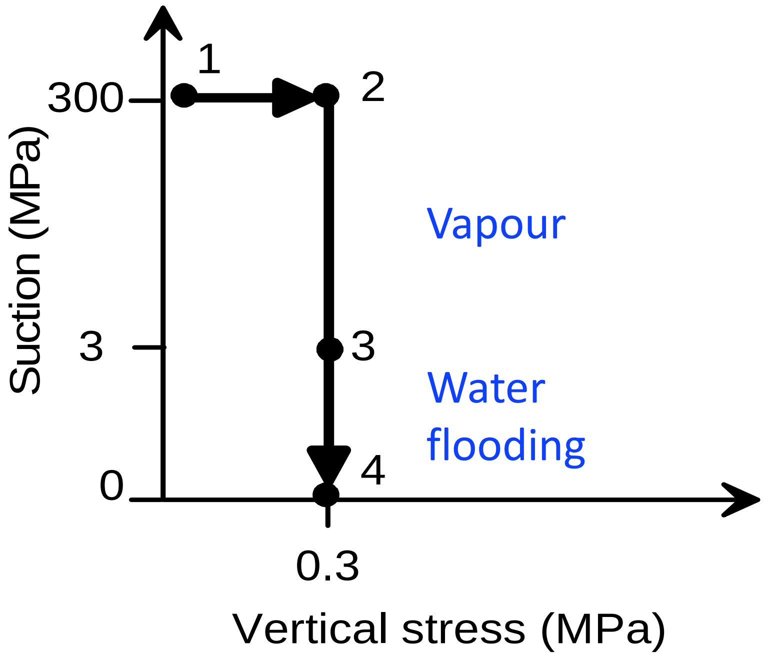


- Two similar loading-wetting paths imposed to a pellet sample $\rho_d = 1.3 Mg / m^3$

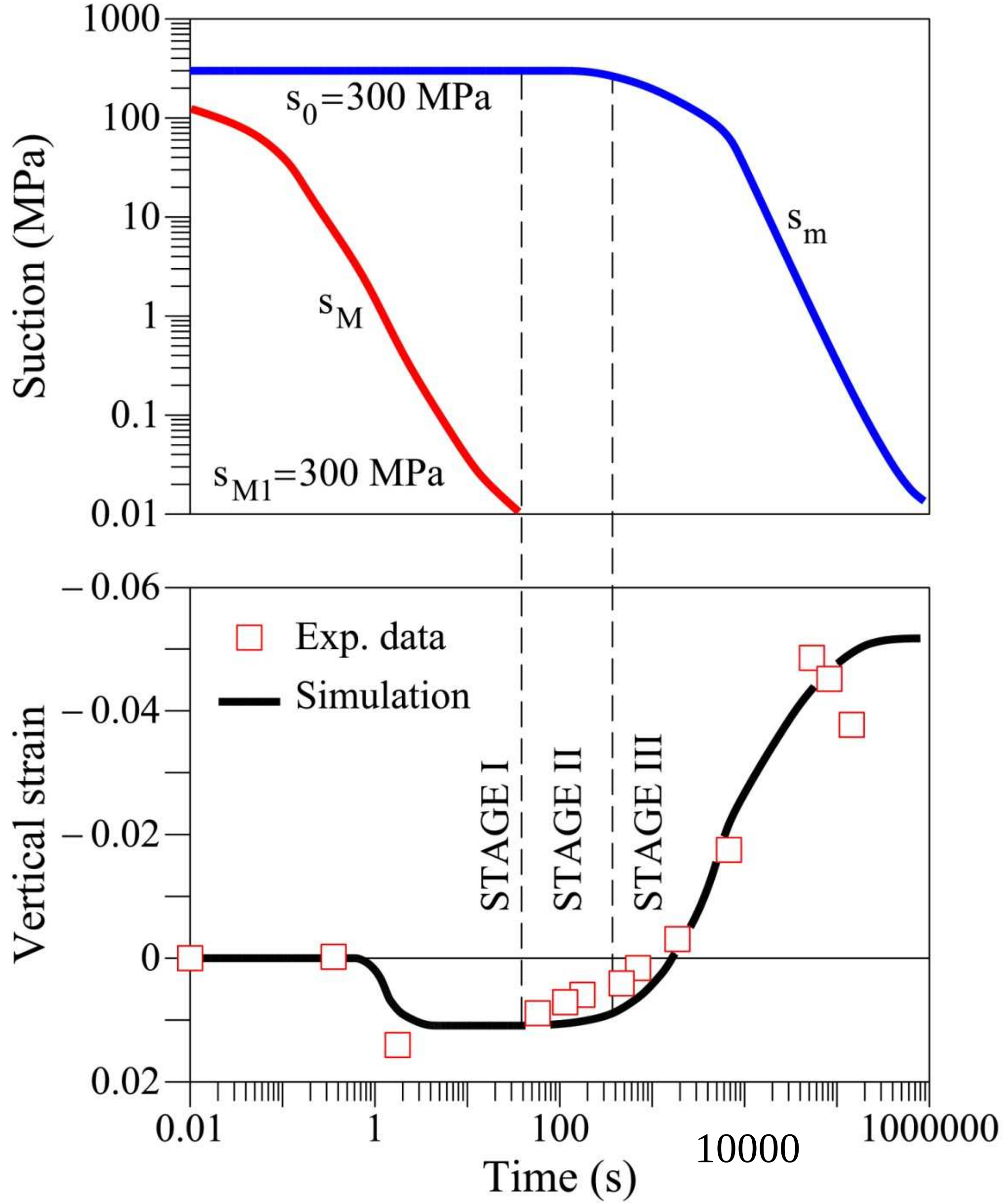
Fast wetting. Liquid injection 2 → 4



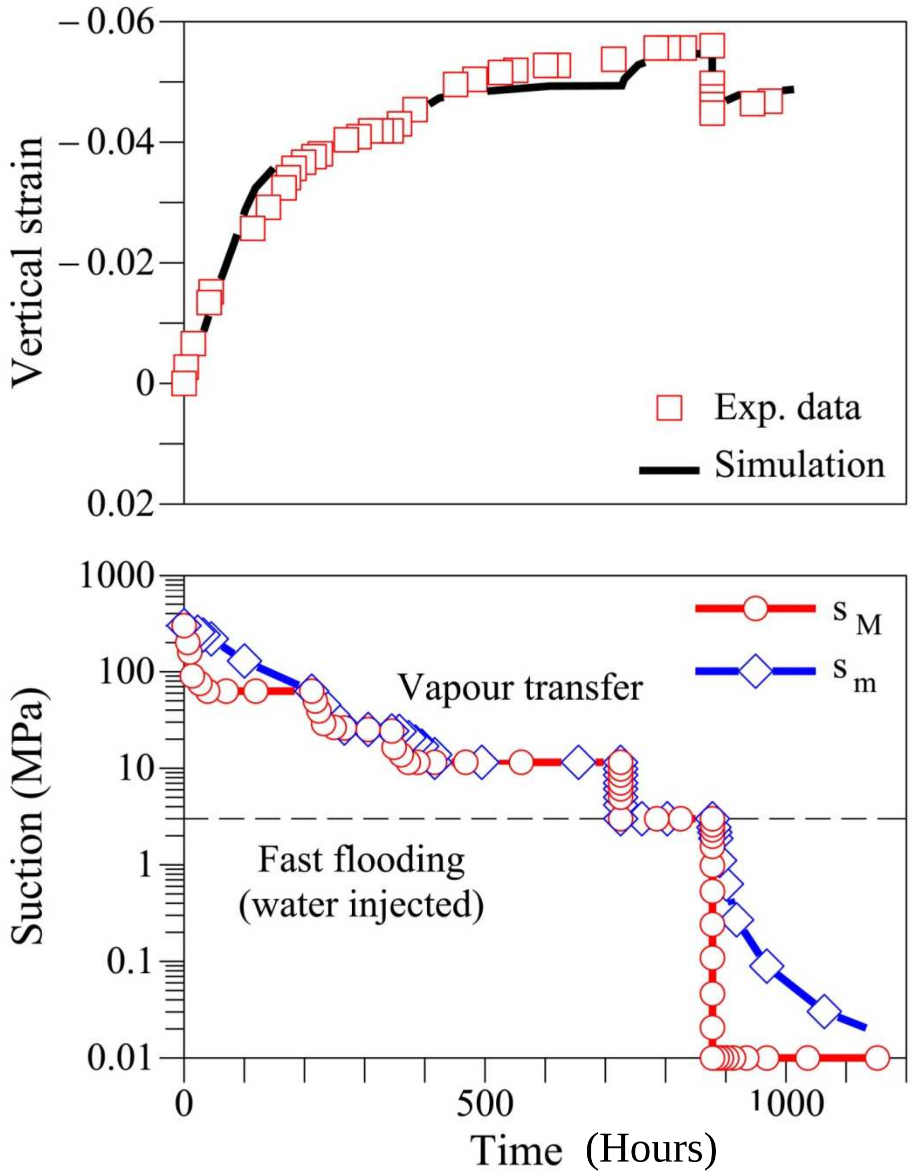

Slow wetting. Vapour equilibrium 2 → 3



# ▪ Modelling the fast wetting test



# ▪ Modelling the slow wetting test



# CONCLUDING REMARKS

- Extreme variety of unsaturated soils

## CONCLUDING REMARKS

- Extreme variety of unsaturated soils
- A variety of deformation mechanisms

CONCLUDING REMARKS

- Extreme variety of unsaturated soils
- A variety of deformation mechanisms
- Is there any thing in common?      The concept of water energy (suction)

# CONCLUDING REMARKS

- Extreme variety of unsaturated soils
- A variety of deformation mechanisms
- Is there any thing in common? The concept of water energy (suction)
- The relevance of soil microstructure

# CONCLUDING REMARKS

- Extreme variety of unsaturated soils
- A variety of deformation mechanisms
- Is there any thing in common? The concept of water energy (suction)
- The relevance of soil microstructure
- Challenge: Introduce microstructure and its evolution into constitutive modelling

# CONCLUDING REMARKS

- Extreme variety of unsaturated soils
- A variety of deformation mechanisms
- Is there any thing in common? The concept of water energy (suction)
- The relevance of soil microstructure
- Challenge: Introduce microstructure and its evolution into constitutive modelling
- One way explored: Inserting microstructure into the definition of "effective stresses". It may lead to simple but powerful models

# CONCLUDING REMARKS

- Extreme variety of unsaturated soils
- A variety of deformation mechanisms
- Is there any thing in common?      The concept of water energy (suction)
- The relevance of soil microstructure
- Challenge: Introduce microstructure and its evolution into constitutive modelling
- One way explored: Inserting microstructure into the definition of "effective stresses".      It may lead to simple but powerful models
- Equilibrium of local suction not always guaranteed

THANK YOU!