Variation de la microstructure des argiles remaniées sous chargement triaxial en relation avec le phénomène de la dilatance

Qianfeng GAO (LEM3-UL), **Mahdia HATTAB** (LEM3-UL), **Jean-Marie Fleureau** (MSSMat-CentraleSupélec),
Pierre-Yves HICHER (GeM-EC Nantes)

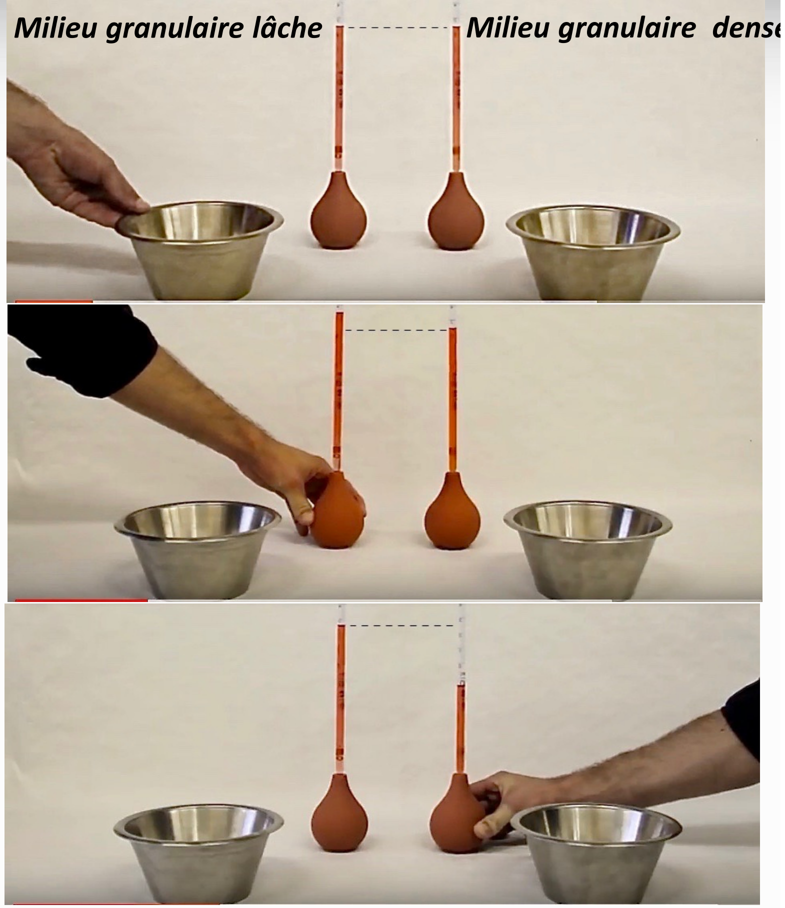
Journée CFMS & CFMR " Microstructure des sols et des roches argileux – Conséquences pour l'ingénieur *25 octobre 2018*

Partie 1 – Etude expérimentale

Partie 2 – Modélisation Micromécanique

Phénomène de Dilatance- Dilatance de Reynolds

Illustration de G. Mollon
INSA Lyon (2015)

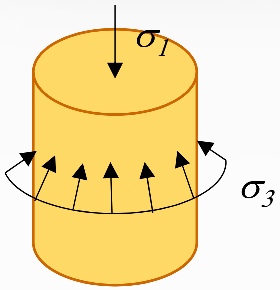


Faculty of Civil Engineering RWTH
Aachen University

Phénomène de Liquéfaction

Effondrement par Liquéfaction.
Séisme de Niigata (1964) – (USGS)

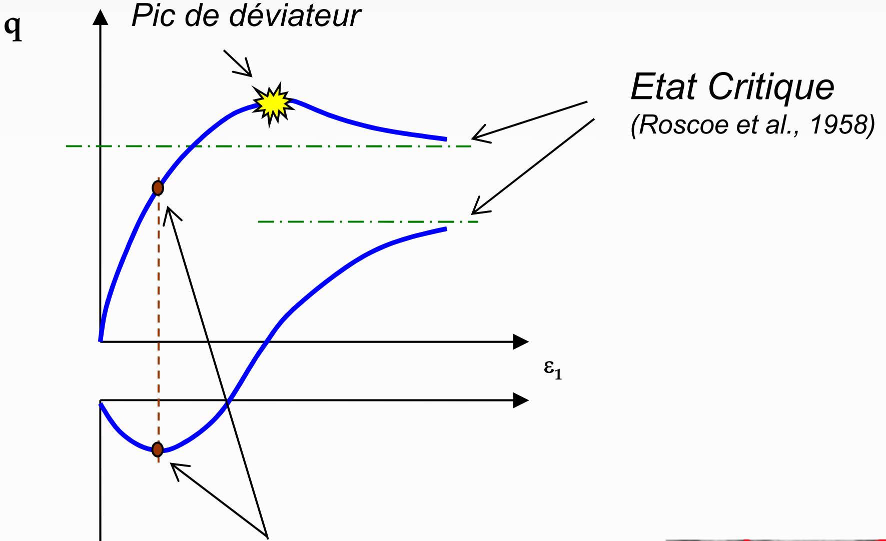
Objectifs



$$p' = \frac{\sigma'_1 + 2\sigma'_3}{3}$$

$$q = \sigma'_1 - \sigma'_3$$

$$Cas\ de\ OCR > 2$$



Etat Critique

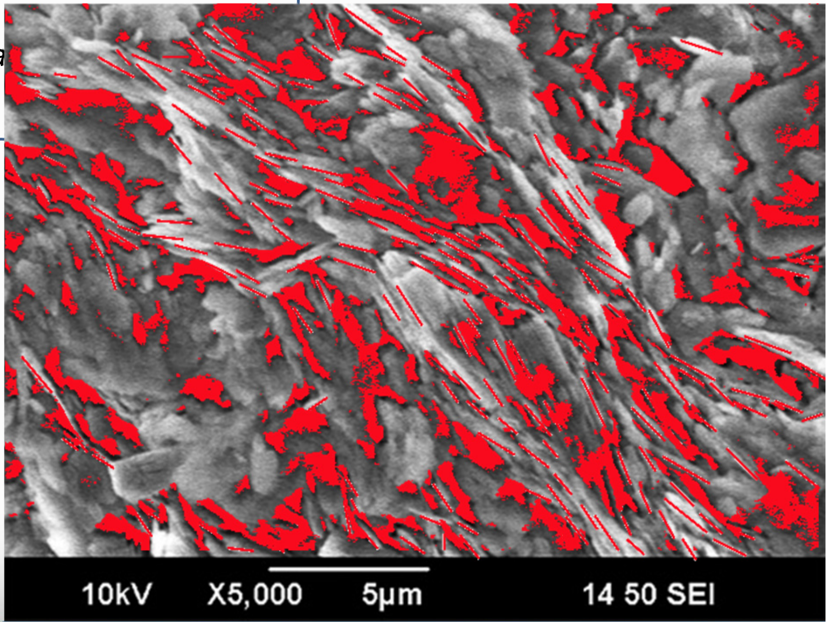
(Roscoe et al., 1958)

Etat caractéristique (phénomène d'appa

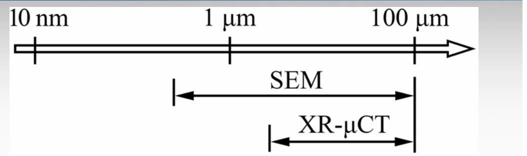
de la dilatance – Luong 1978)

Comportement typique ***des argiles saturées remaniées surconsolidées*** *sur chemin triaxial classique*

Identifier les mécanismes qui s'activent au niveau local pour les relier au comportement macroscopique



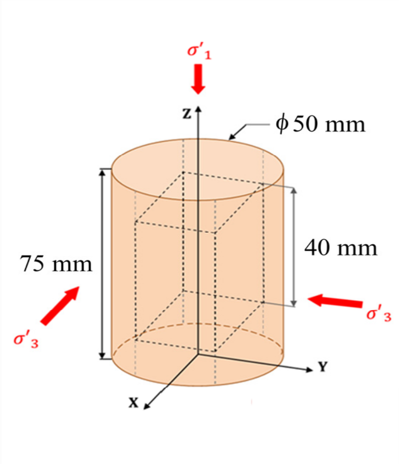
Approche expérimentale pour une investigation Micro-Macro

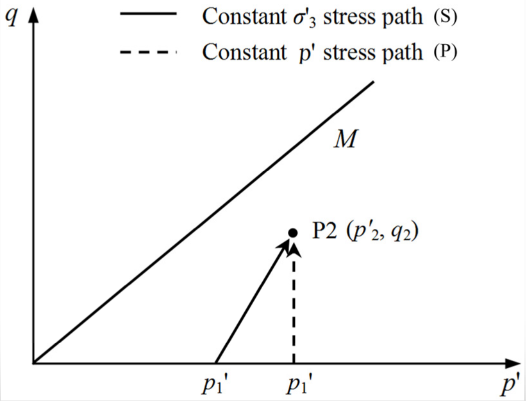


Essais Mécaniques

Observations Microscopiques

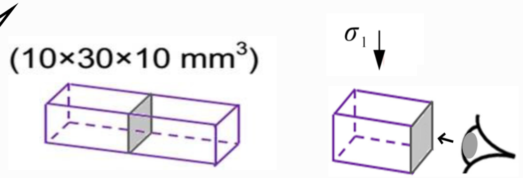
Essais triaxiaux
drainés

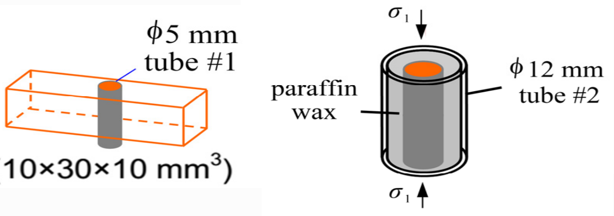




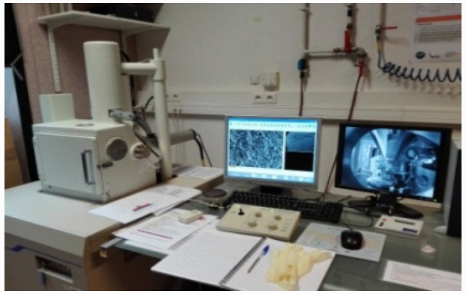
Microscopie Electronique à Balayage
Observations au MEB

X-ray Microtomography
(XR-µCT) scans



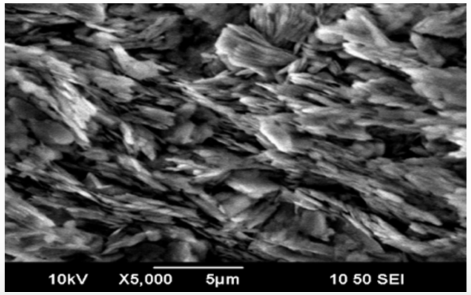


Lyophilisation, Fracture, Métallisation

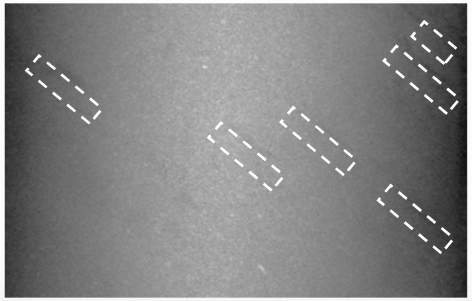


JSM-6490 (JEOL)

Haute Resolution 3D µCT (XR-Solutions)



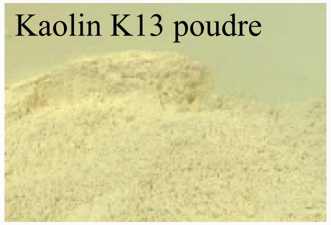
Images MEB

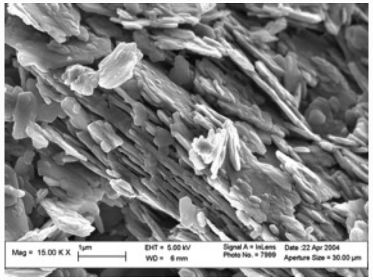


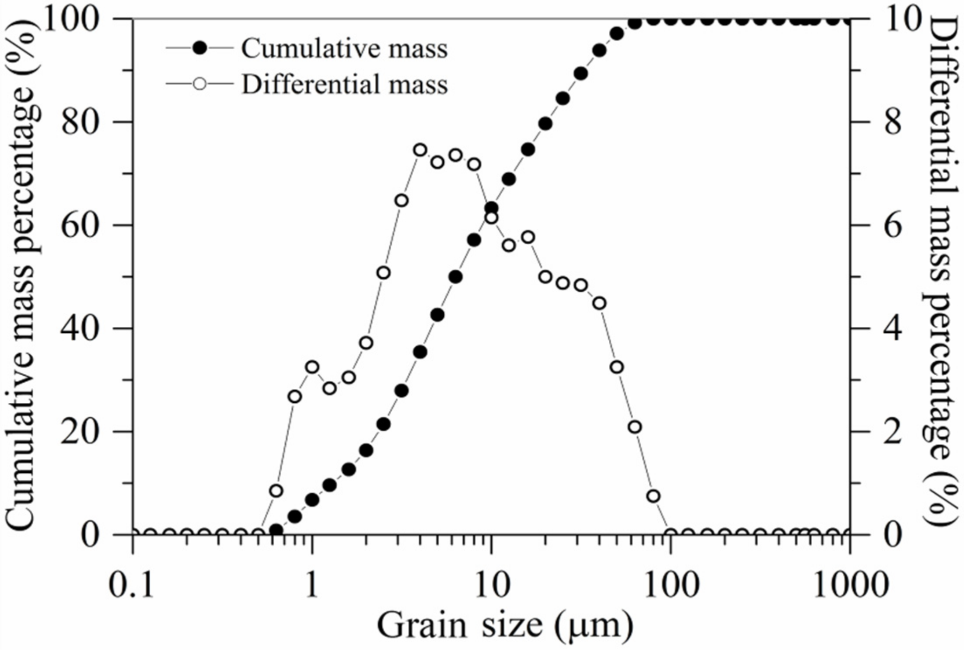
CT projection

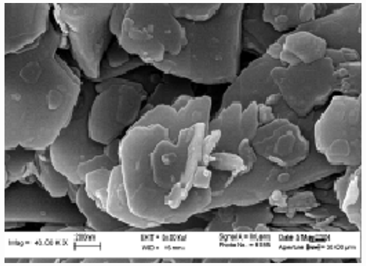
Propriétés du matériau modèle

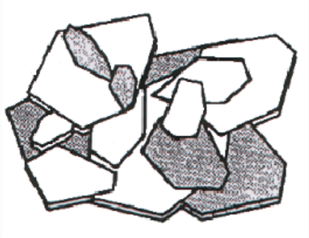
Matériau	Limite de liquidité w_L (%)	Limite de plasticité w_P (%)	Indice de plasticité I_p (%)	Densité des grains solides ρ_s/ρ_w	Indice de compression Cc	Indice de gonflement Cs
Kaolin K13	42	21	21	2.63	0.28	0.09



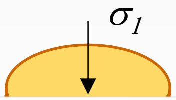




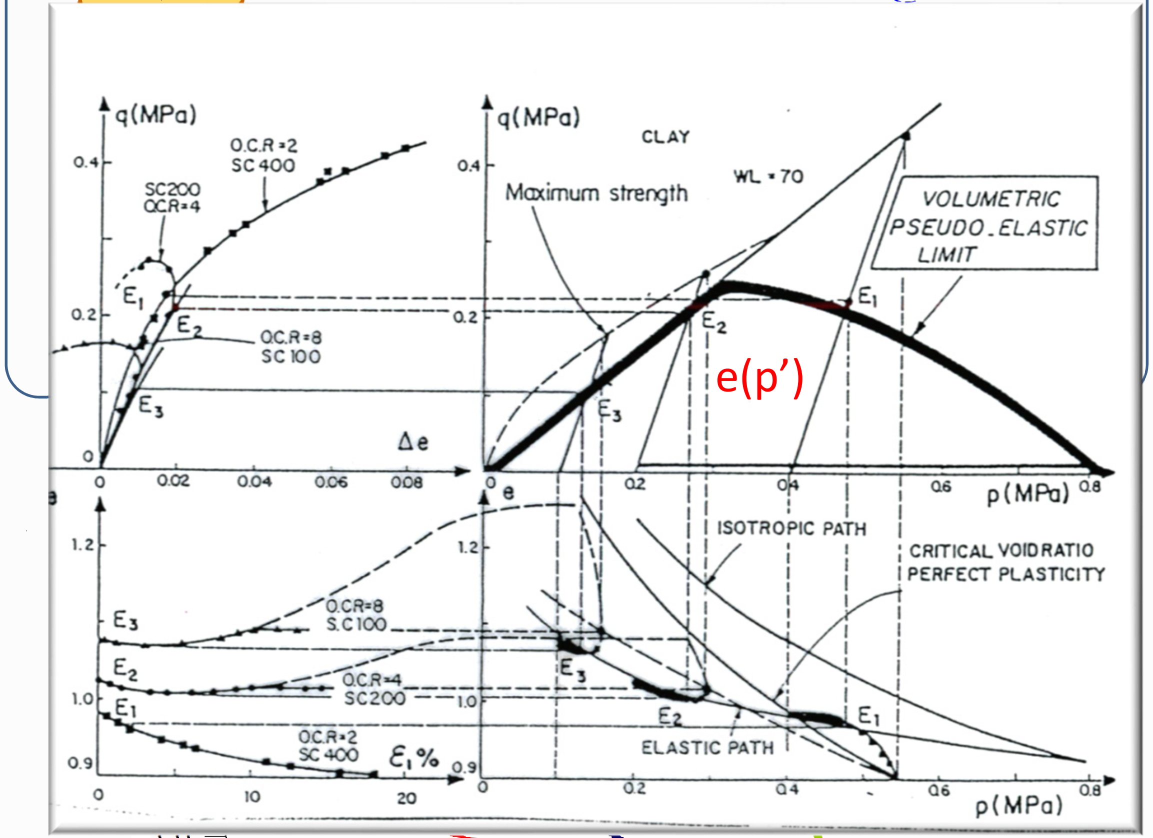


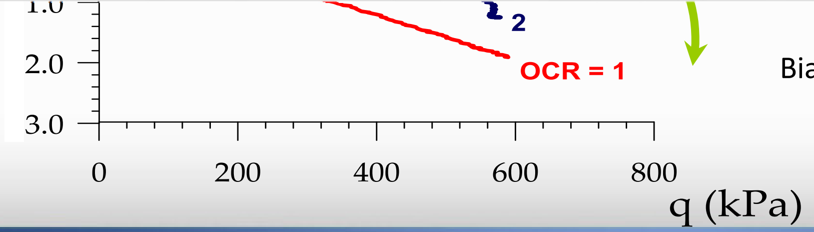


Cadre formel de l'élastoplasticité



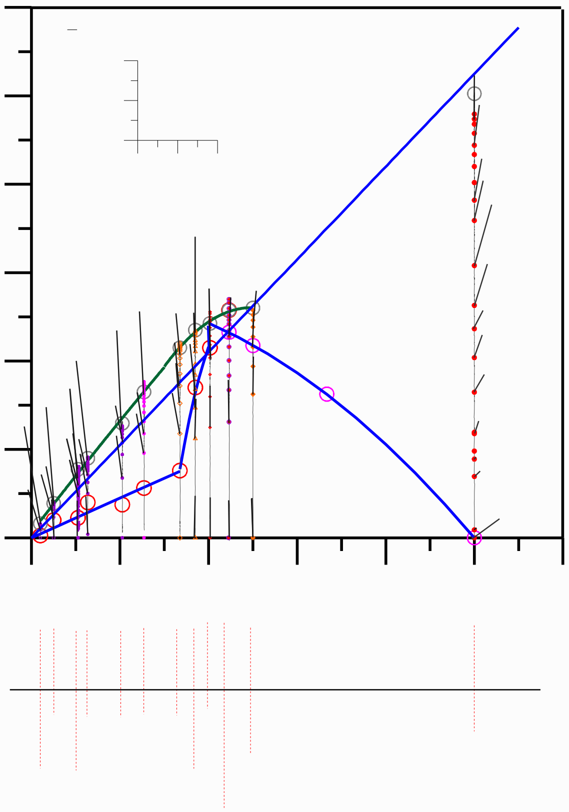
$$\sigma'_{ij} = p'\delta_{ij} + q\,\partial_{ij} \qquad \varepsilon_{ij} = \frac{1}{3}\varepsilon_v\,\delta_{ij} + \bar{\varepsilon}\,d_{ij}$$



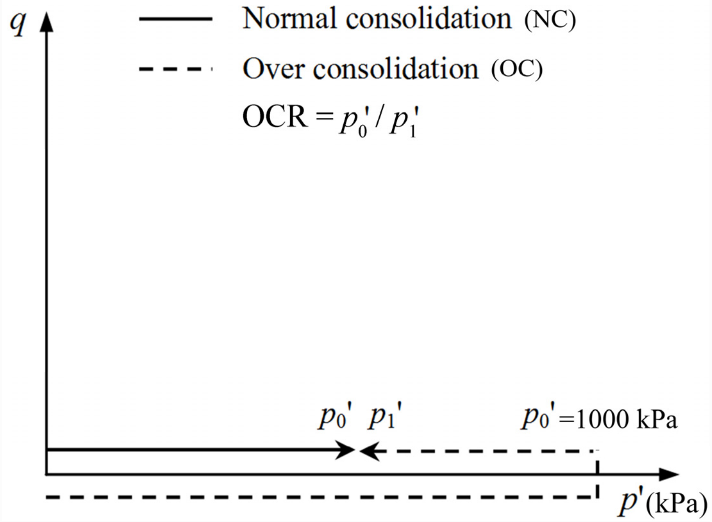


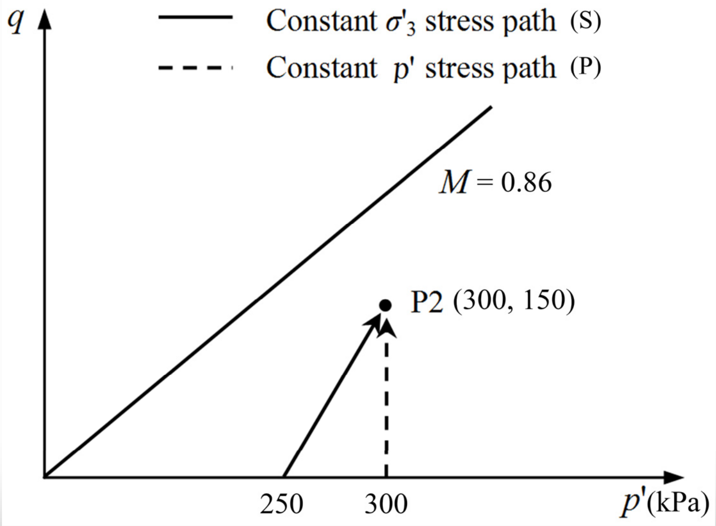
Biarez and Hicher (1994)

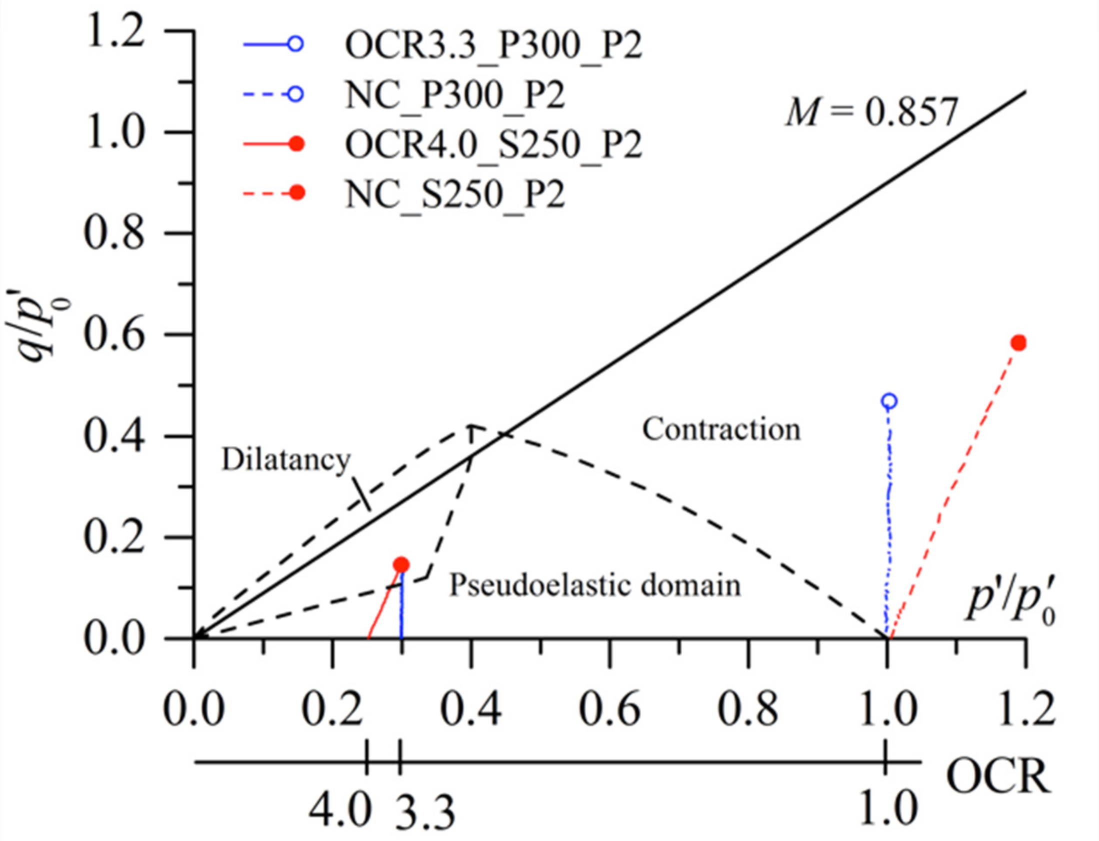
Hattab M, Hicher P-Y (2004)



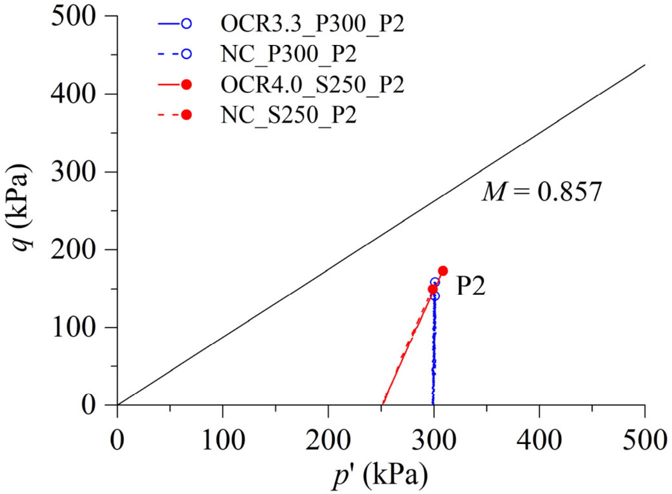
Cadre de l'étude

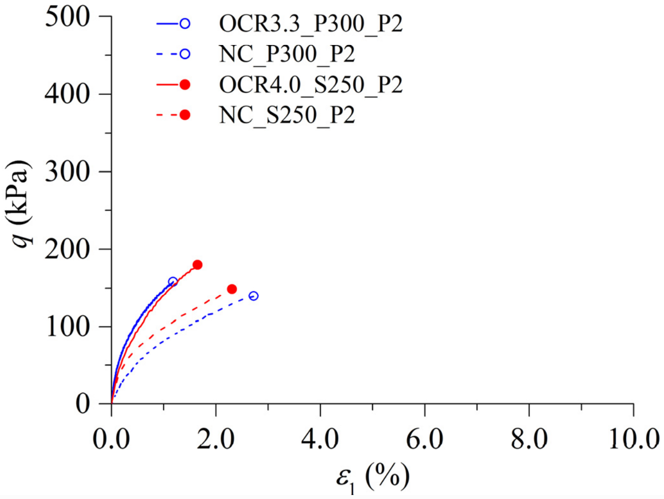


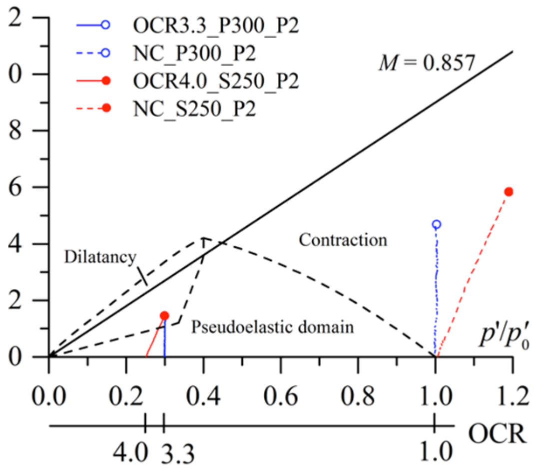


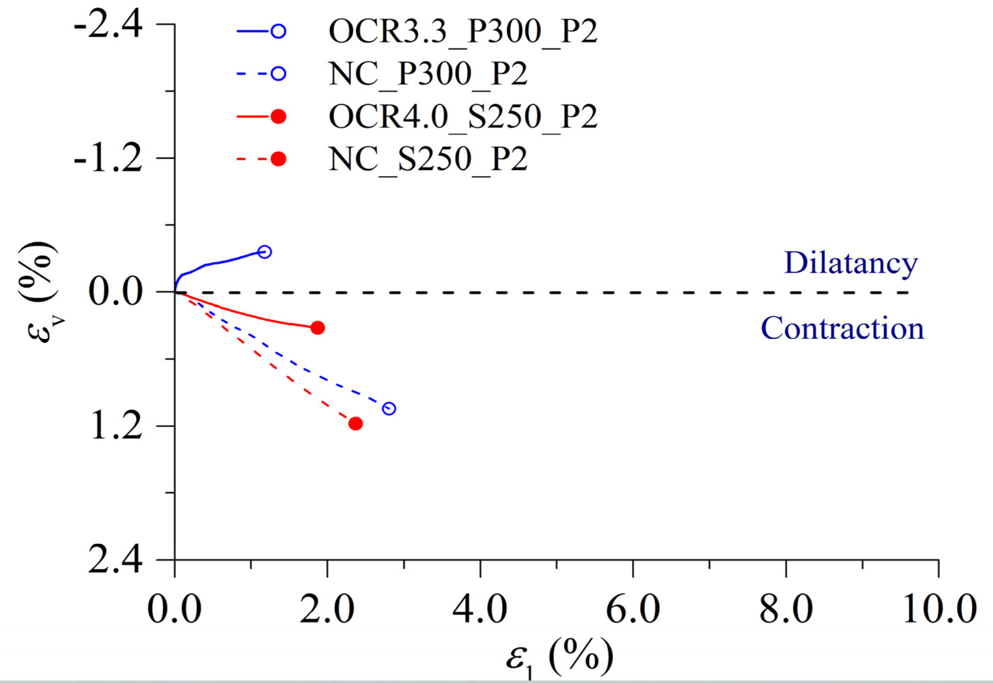


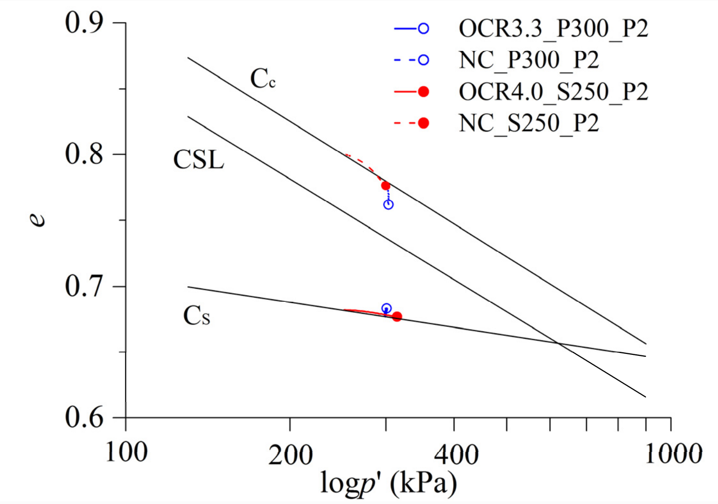
Comportement mécanique - Influence du chemin des contraintes







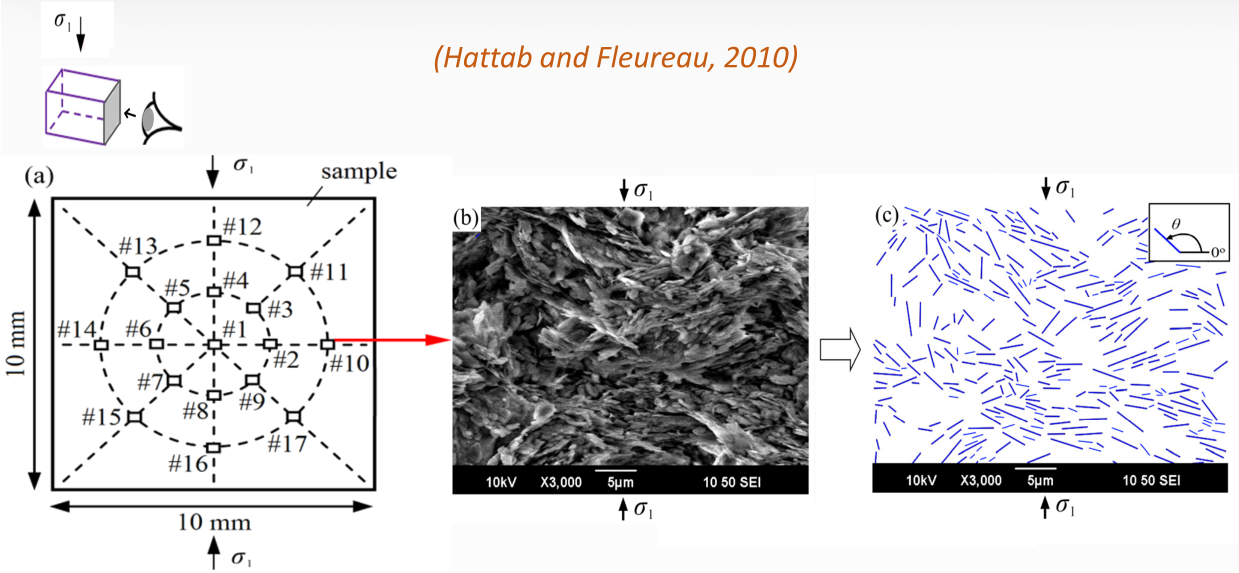




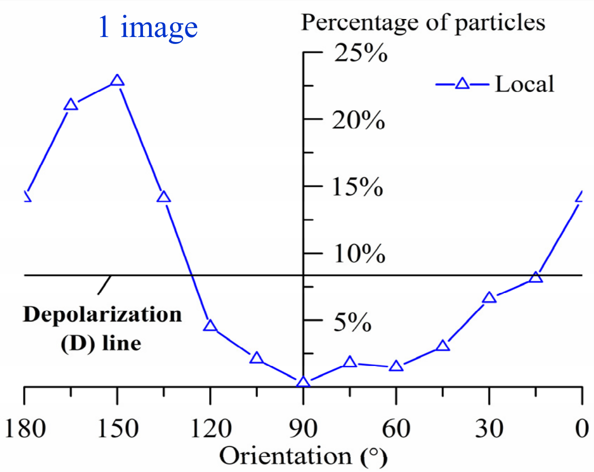
Ighil Ameur L., Gao Q. (2016)

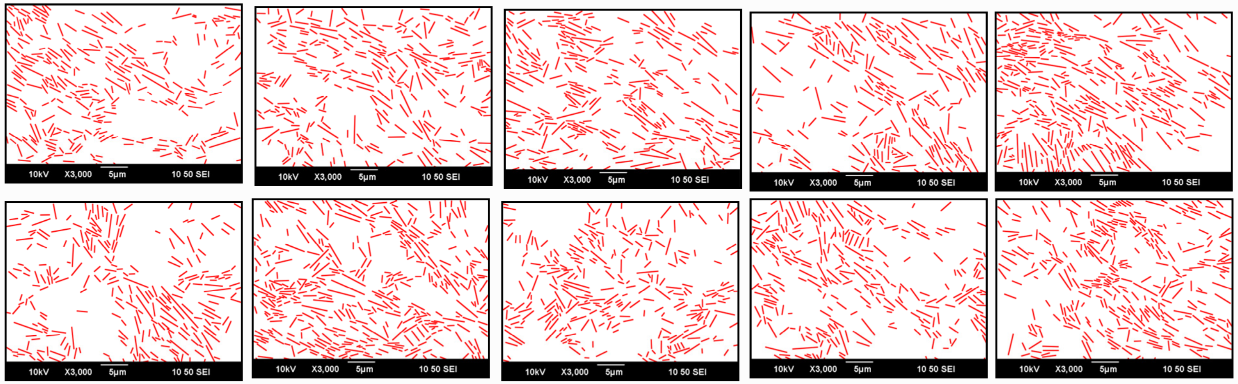
Caractérisation de la Microstructure – Orientation des particules (MEB)

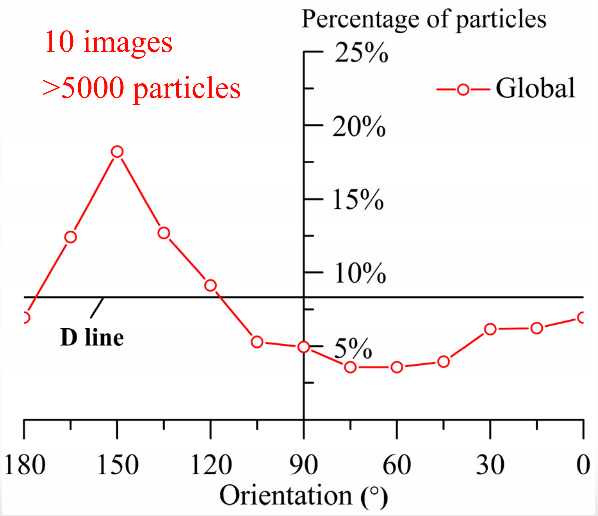
(Hattab and Fleureau, 2010)



(Q. Gao, 2018)

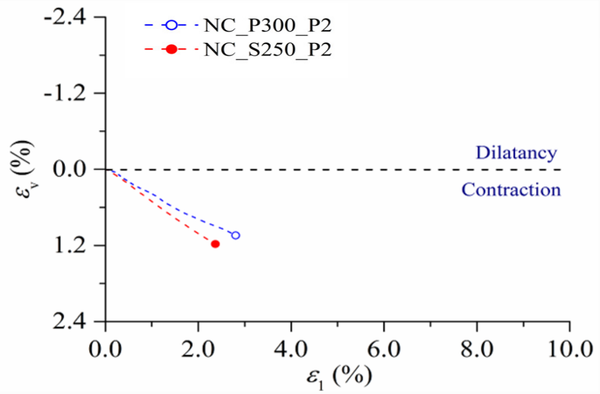




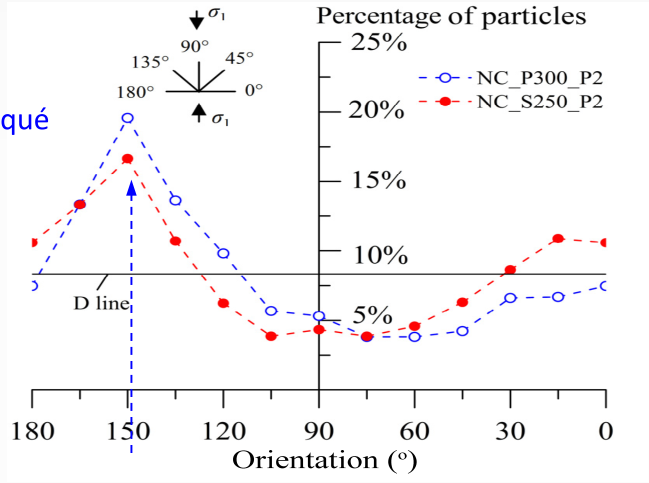


Caractérisation de la Microstructure – Orientation des particules (MEB)

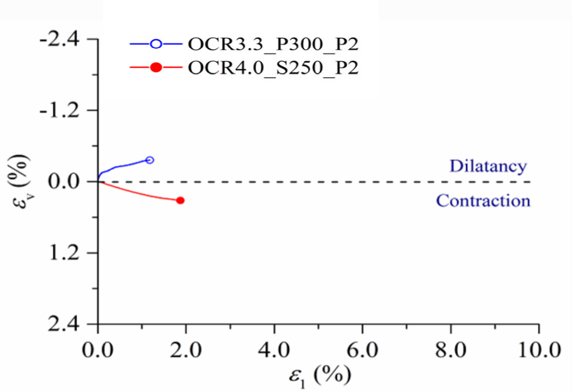
Cas normalement consolidé



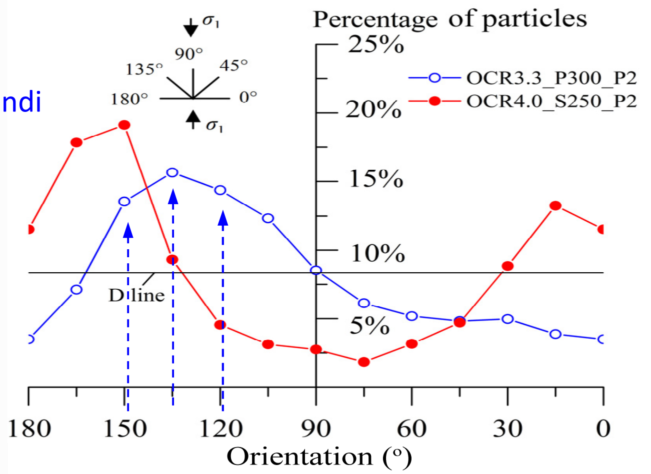
Pic marqué



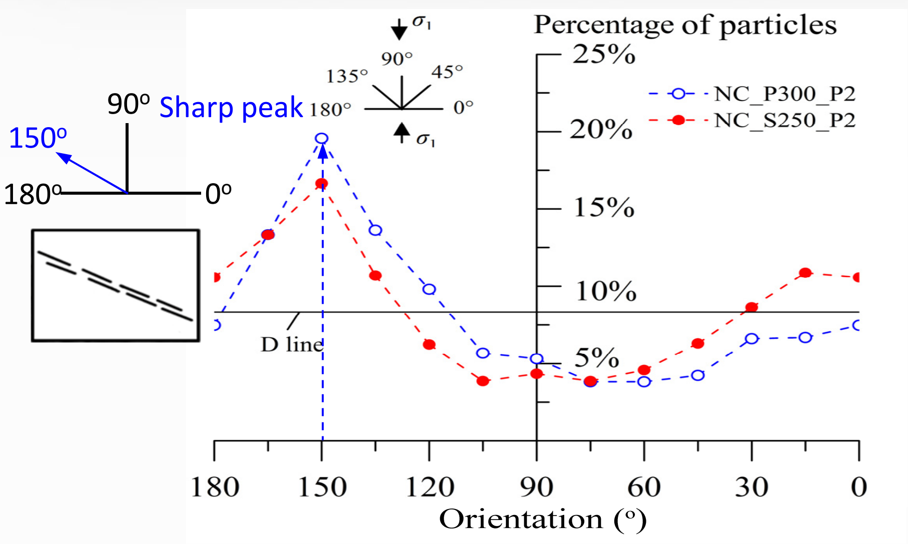
Cas surconsolidé

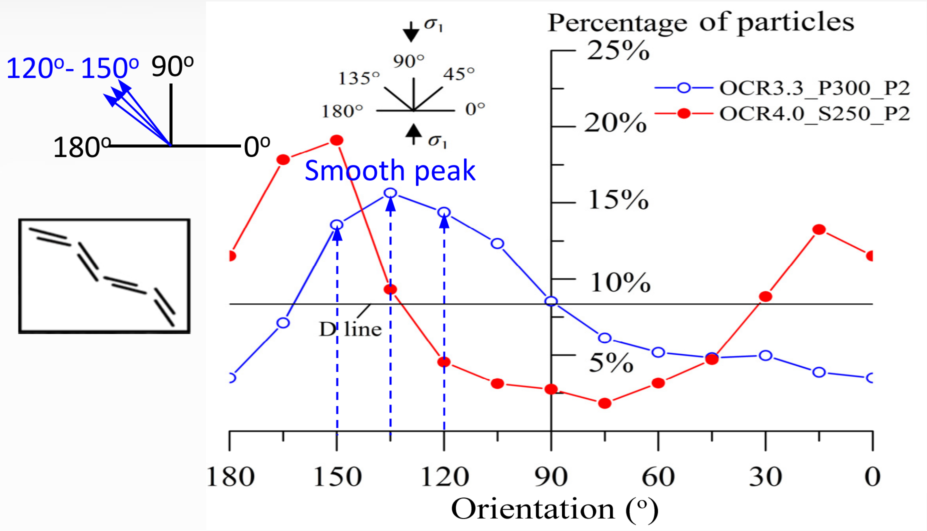


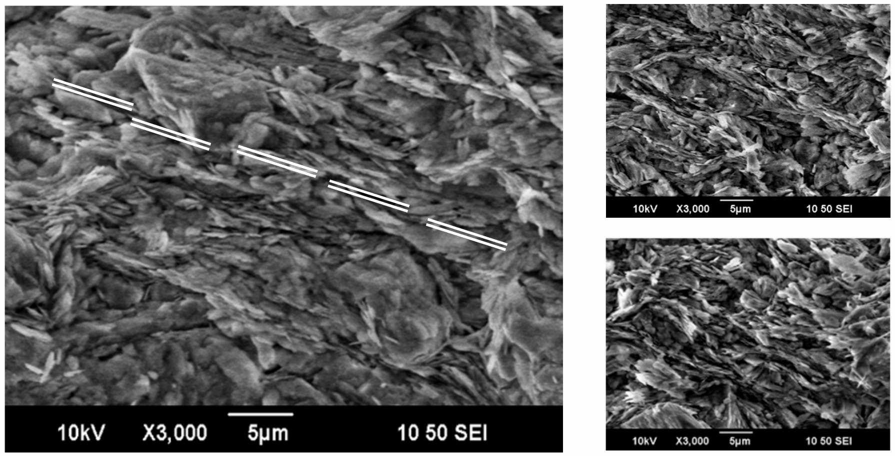
Pic arrondi



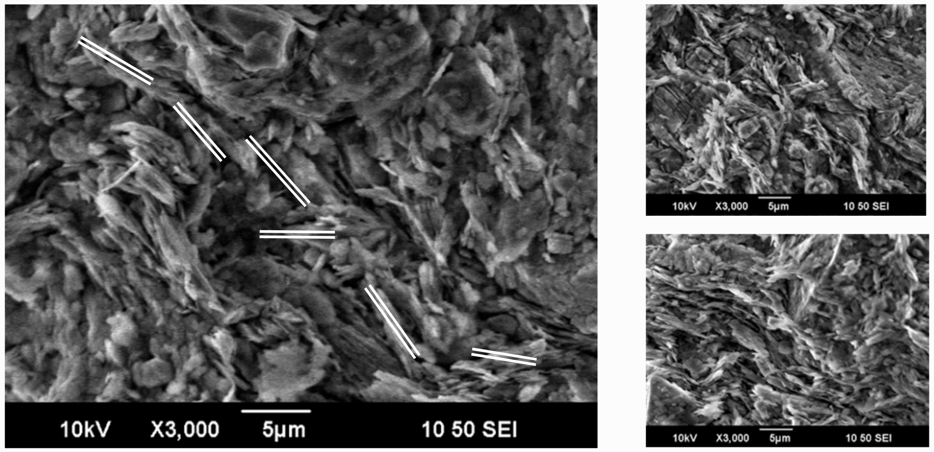
Caractérisation de la Microstructure – Orientation des particules (MEB)







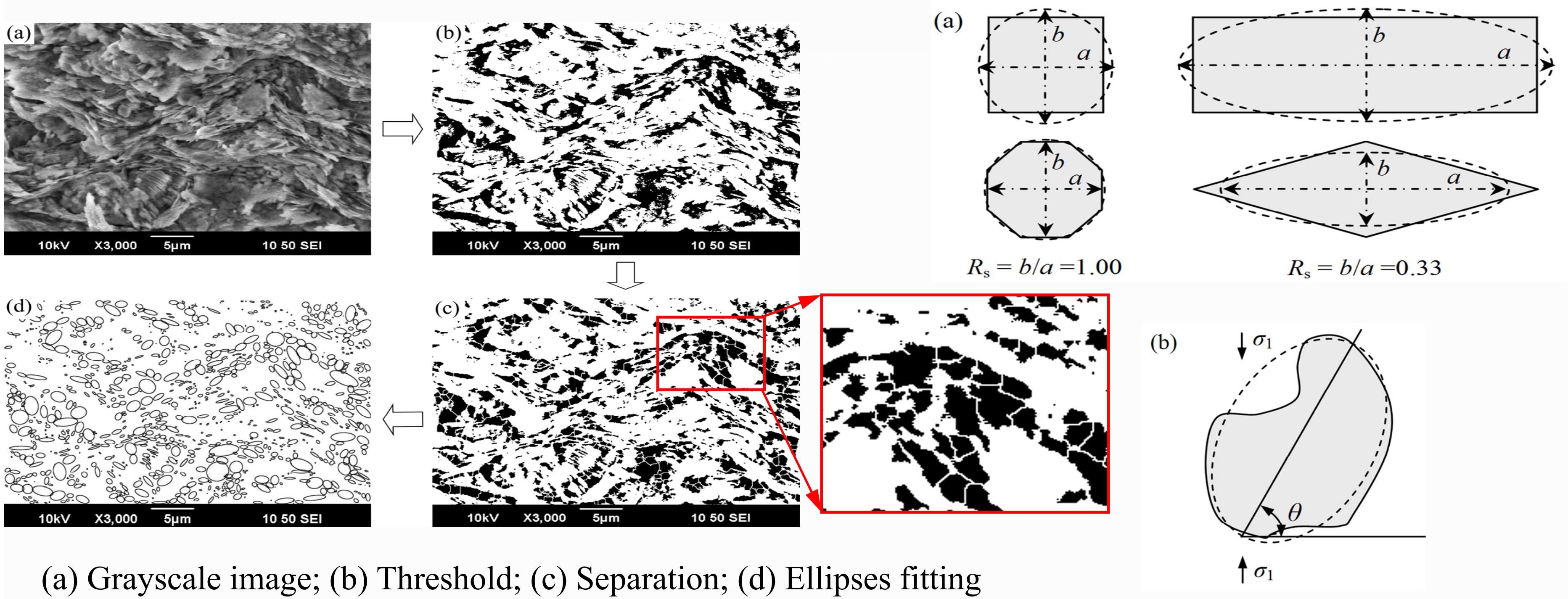
NC_P300_P2



OCR3.3_P300_P2

Caractérisation de la microstructure – Forme et Orientation des pores (MEB)

(Q. Gao, 2018)



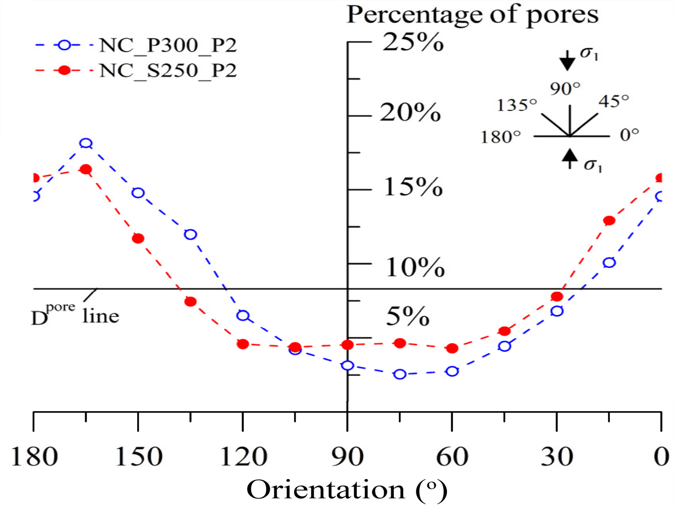
(a) Grayscale image; (b) Threshold; (c) Separation; (d) Ellipses fitting

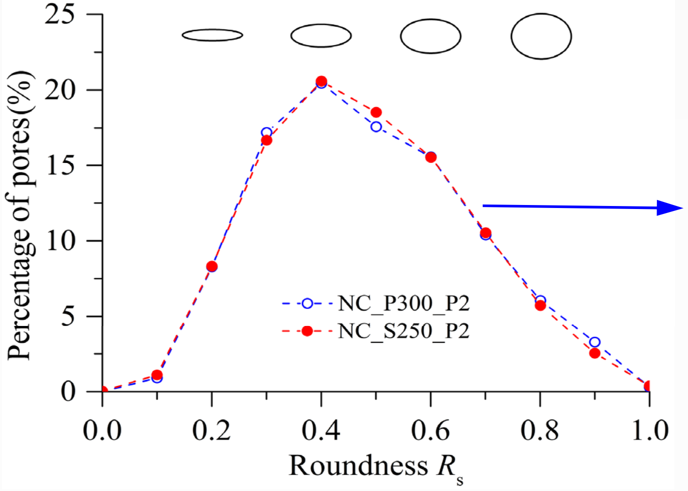
Adjustable watershed algorithm

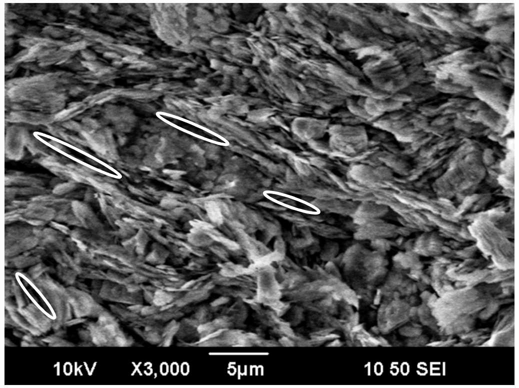
Identification de la géométrie des pores

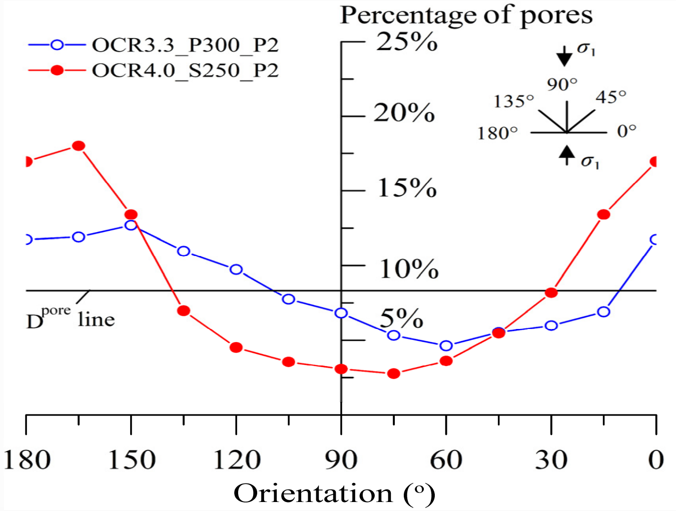
Définition des propriétés des pores
forme et orientation

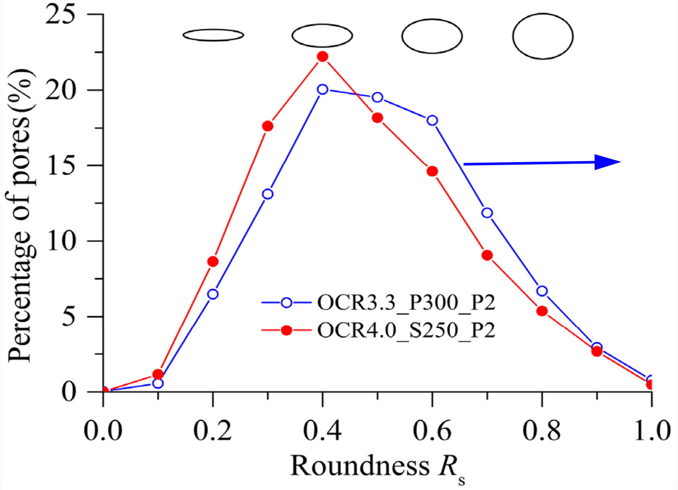
Caractérisation de la microstructure – Forme et Orientation des pores (MEB)

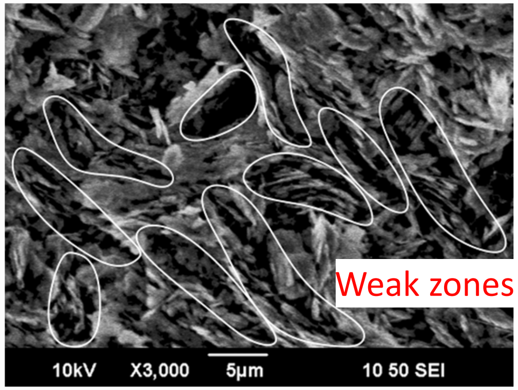




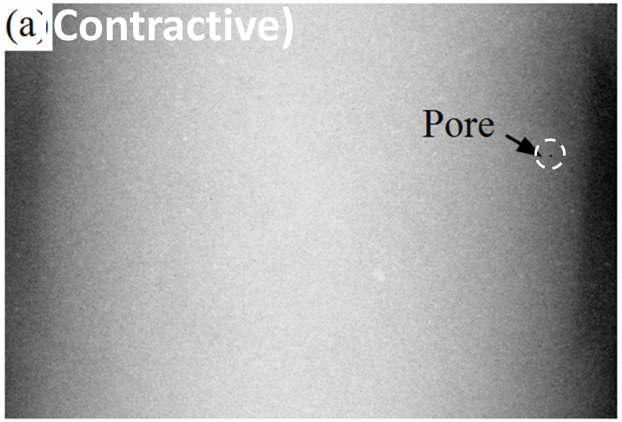




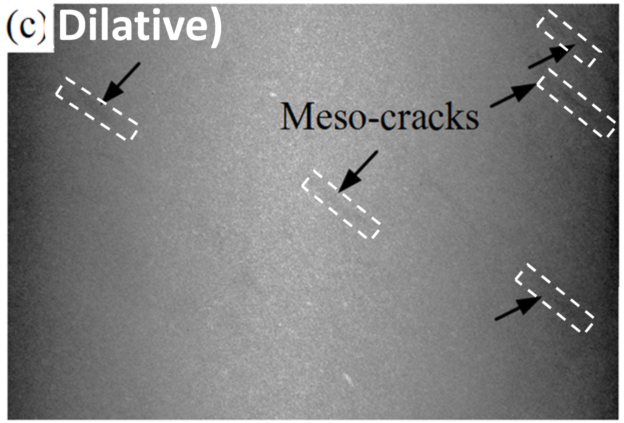




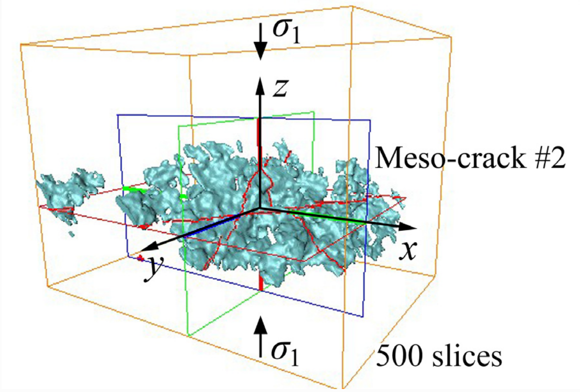
Caractérisation de la microstructure – Microfissuration (Microtomographie)

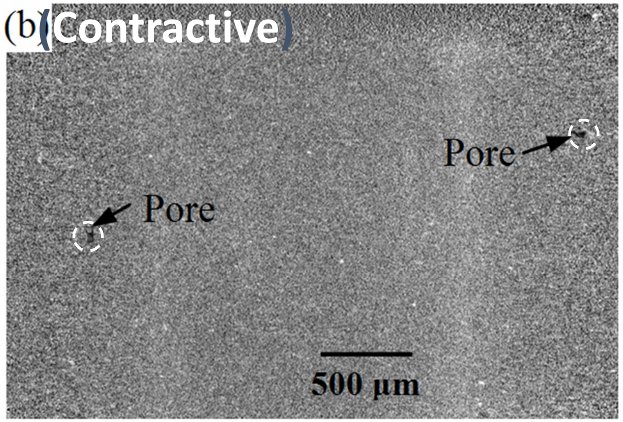


Projection de NC_P300_P2

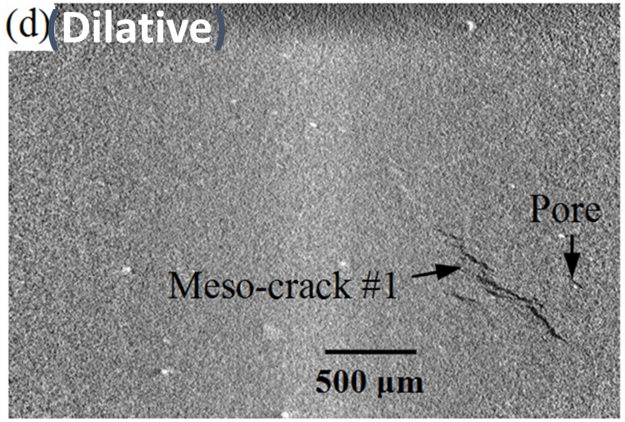


Projection de OCR3.3_P300_P2

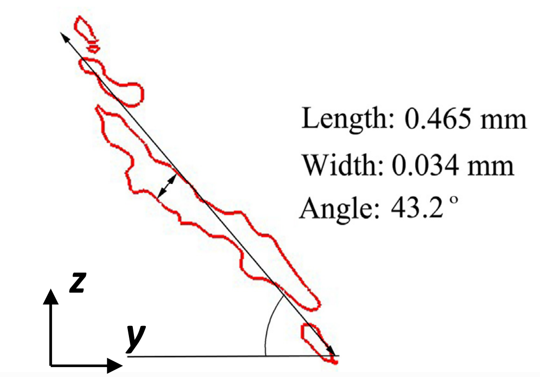




Coupe de NC_P300_P2

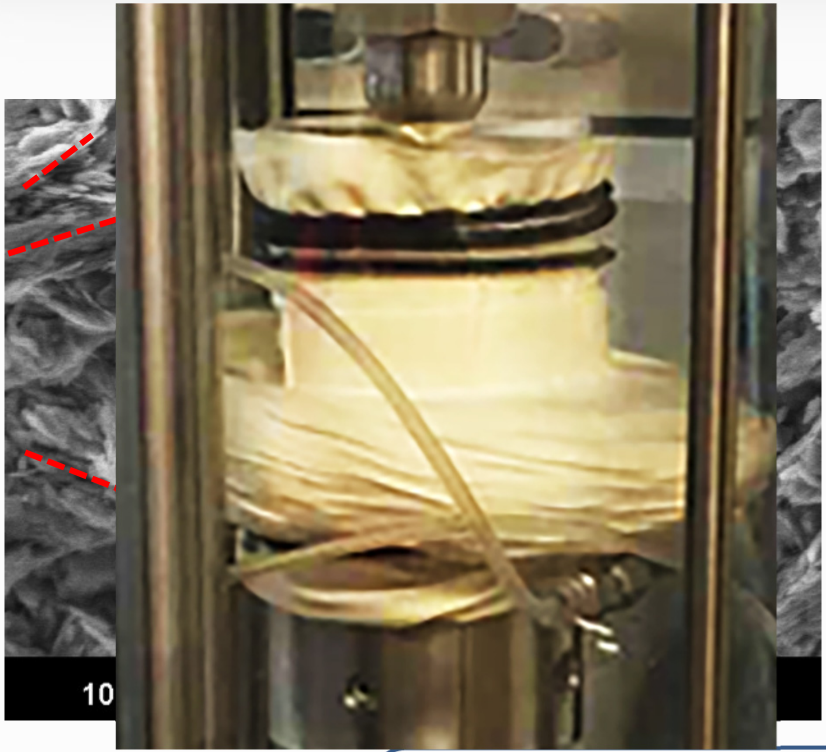


Coupe de OCR3.3_P300_P2

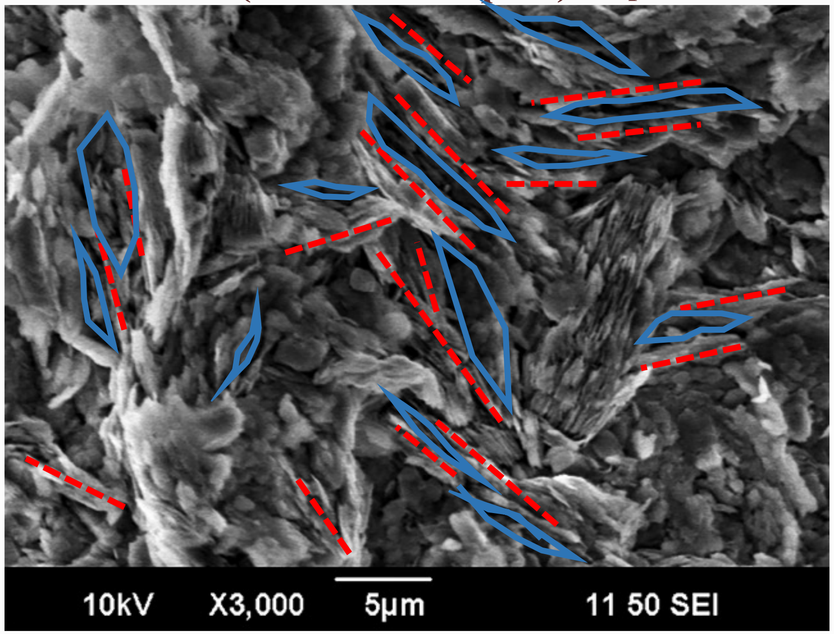


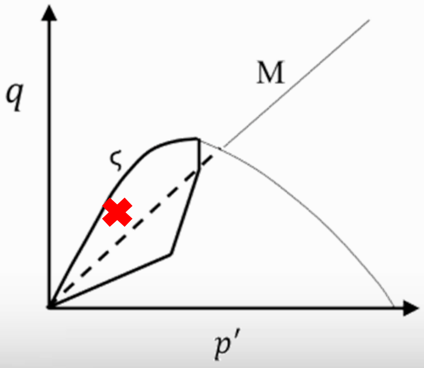
Dilatance et Fluage

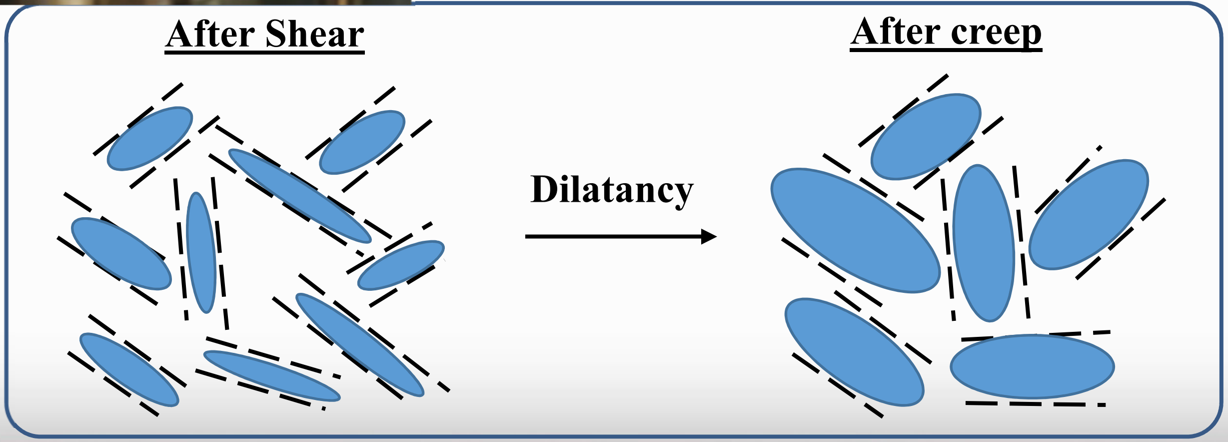
(D. Zhao, 2017)



(P010-OCR4-q200)creep







After Shear

Dilatancy →

After creep

Partie 1 – Conclusions

1 À un niveau de contrainte donné, sur le plan des contraintes, l'argile normalement consolidée présente toujours une contractance; alors que la déformation volumique de l'argile surconsolidée dépend du chemin de contraintes : elle peut être en contractance (chemin classique) ou en dilatance (chemin purement déviatoire).

2 **Au niveau microstructurelle**, le comportement dilatant sur chemin purement déviatorique est associé à une orientation des particules argileuses organisées par groupe, associées face-face le long d'une ligne brisée.

3 Les propriétés des pores sont tout à fait cohérents avec l'orientation des particules, ils sont en forme elliptiques, plutôt ouverts, formant des micro-zones ou peut s'activer le mécanisme de glissement. A un niveau de contrainte proche de la rupture, le fluage provoque un effondrement brutal de l'éprouvette.

4 **Le phénomène de dilatance dans les argiles remaniées saturées est gouverné par le développement d'une microfissuration plus ou moins orientée plus ou moins ouverte, et qui peut se propager jusqu'à l'échelle mésoscopique.**

Partie 2 –Modélisation Micromécanique

Approche par le modèle de Chang-Hicher (2005)

Comportement sur chemin
isotrope

Approche micromécanique

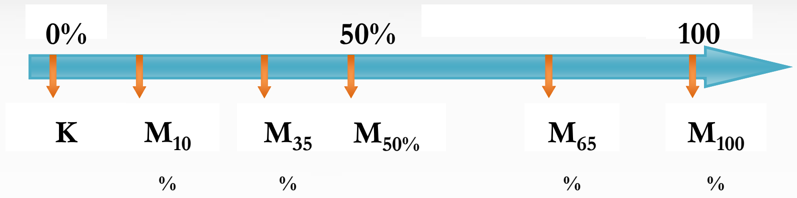
✓ Mécanismes locaux : introduire les propriétés physicochimiques à travers des forces répulsives and attractives agissant entre clusters

✓ Nécessite une validation sur un matériau dont la minéralogie est variable : V2M mélange de Montmorillonite et de Kaolinite

Ching-Shung CHANG
cchang@engin.umass.edu

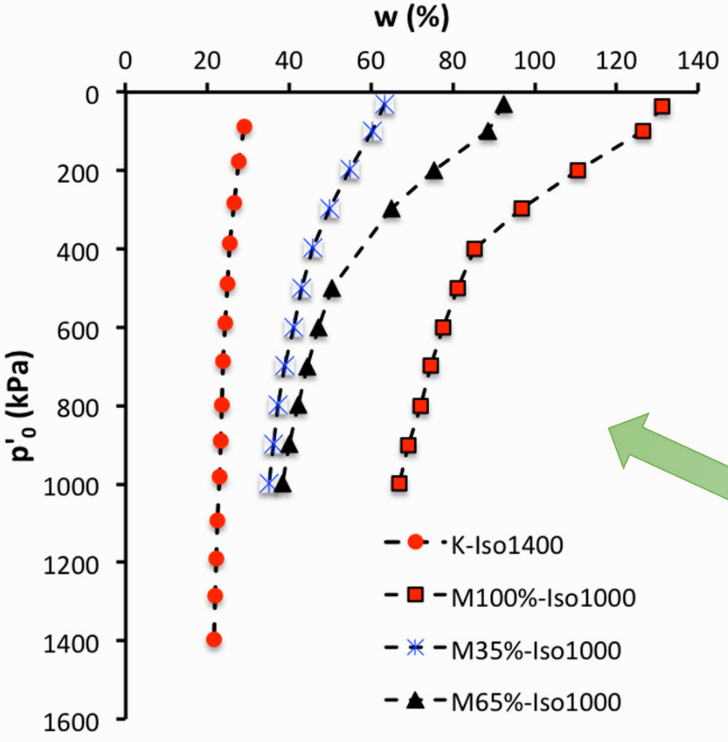
Hattab M, Chang C-S. (2015) « Inter-aggregate forces and energy potential effect on clay deformation »

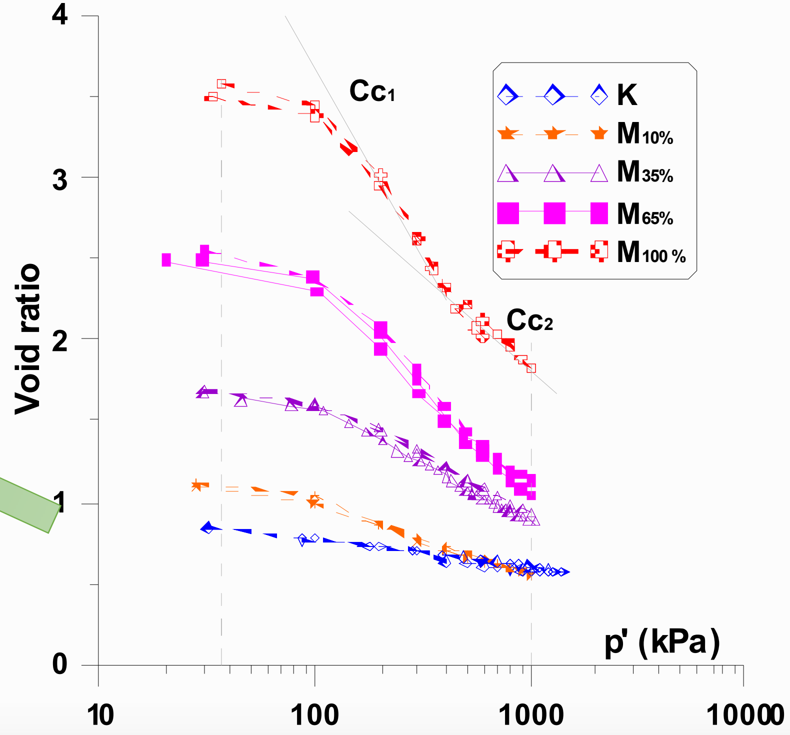
Isotropic paths and Mineralogy variation



V2M : Kaolin/Montmorillonite mixture

(saturated and reconsolidated)





Hammad T, Hattab M, Fleureau J-M, European Journal of Environmental and Civil Engineering (2013)

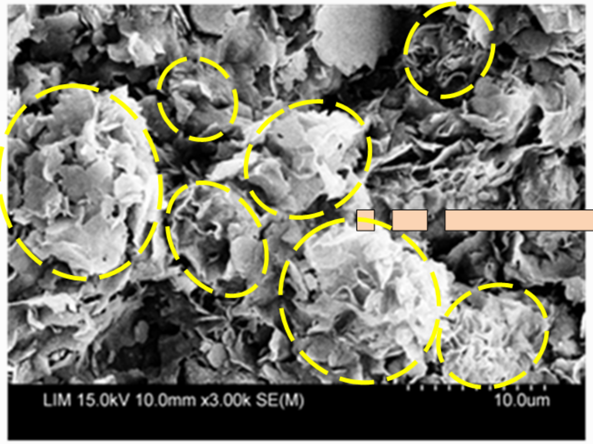
Local properties and Hypothesis

<u>Structure en agrégats des argiles</u> :

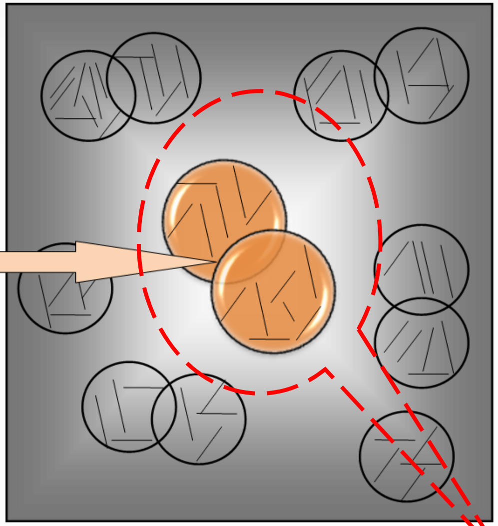
Delage and Lefebvre, 1984,

Hammad et al., 2013,

Hattab et al., 2013



$M_{65\%}$ microstructure (Hammad et al., 2013)

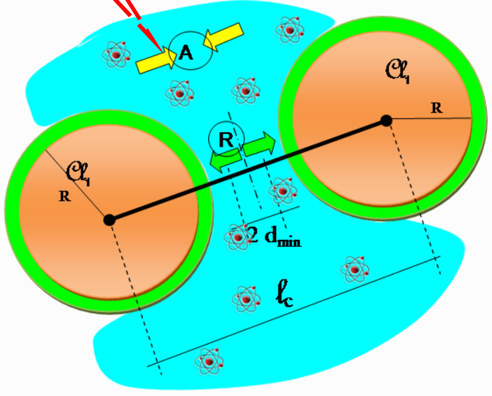


Hypothesis for intercluster interactions:

1- Deformation of the assembly is primarily caused by the change of inter-cluster pores. Clusters are considered as no deformable bodies.

2- Interacting forces exist between two neighboring clusters and between water and the charged surface of clusters.

3-Two types of interacting forces: electrical repulsive and attractive similar to the van der Waals forces. Both contribute to the interclusters normal force.

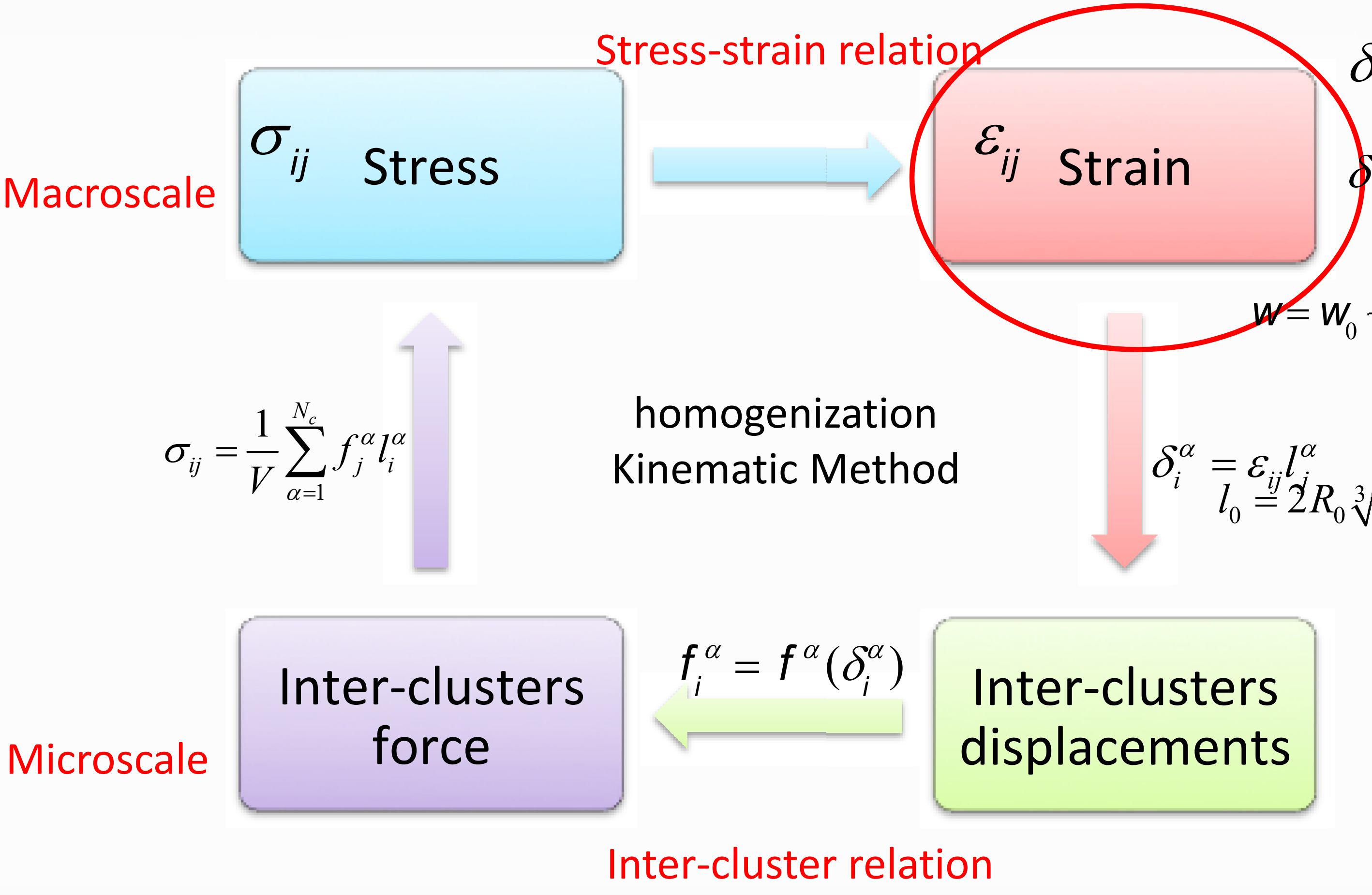


Elementary system definition:
cluster/water/cluster

Micromechanical approach

Micromechanical modeling by Chang (1988),
Chang and Liao (1994) – Chang and Hicher (2005)

Macrostrain-local displacement



Stress-strain relation

Macroscale

σ_{ij} Stress

ε_{ij} Strain

$$\sigma_{ij} = \frac{1}{V}\sum_{\alpha=1}^{N_c} f_j^\alpha l_i^\alpha$$

homogenization
Kinematic Method

$$\delta_i^\alpha = \varepsilon_{ij} l_j^\alpha$$

Microscale

Inter-clusters force

$$f_i^\alpha = f^\alpha(\delta_i^\alpha)$$

Inter-clusters displacements

Inter-cluster relation

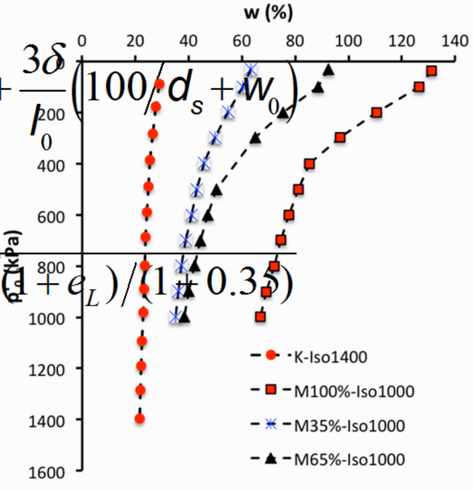
$$\delta_i^\alpha = \varepsilon_{ij} l_j^\alpha$$

$$\delta = \frac{\varepsilon_v l_0}{3}$$

Behaviour on isotropic loading

$$w = w_0 + \frac{3\delta}{l_0}\left(100/d_s + w_0\right)$$

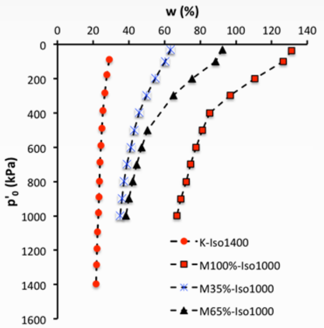
$$l_0 = 2R_0\sqrt[3]{(1+e_L)/(1+0.35)}$$

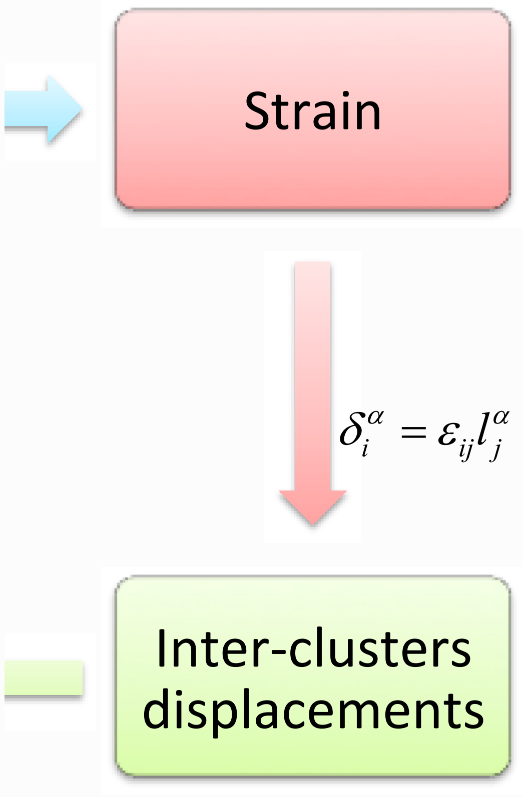


Experimental results

Micromechanical approach

Under isotropic loading conditions

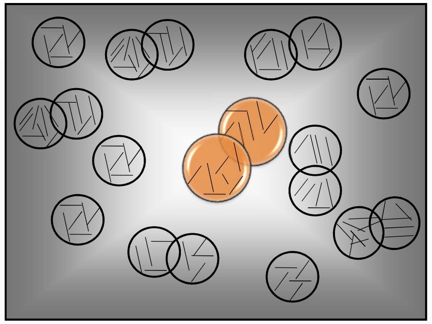


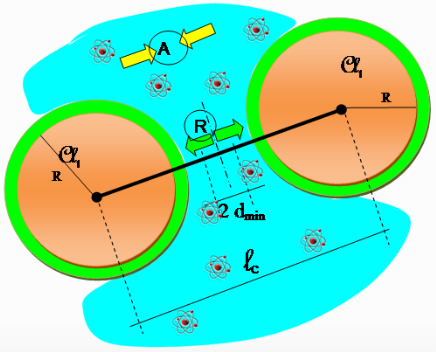


Strain

$\delta_i^\alpha = \varepsilon_{ij} l_j^\alpha$

Inter-clusters displacements





Macrostrain-local displacement

$$\delta_i^\alpha = \varepsilon_{ij} l_j^\alpha$$

$$\delta = \frac{\varepsilon_v l_0}{3}$$

$$w = w_0 + \frac{3\delta}{l_0}\left(100/d_s + w_0\right)$$

$$l_0 = 2R_0\sqrt[3]{(1+e_L)/(1+0.35)}$$

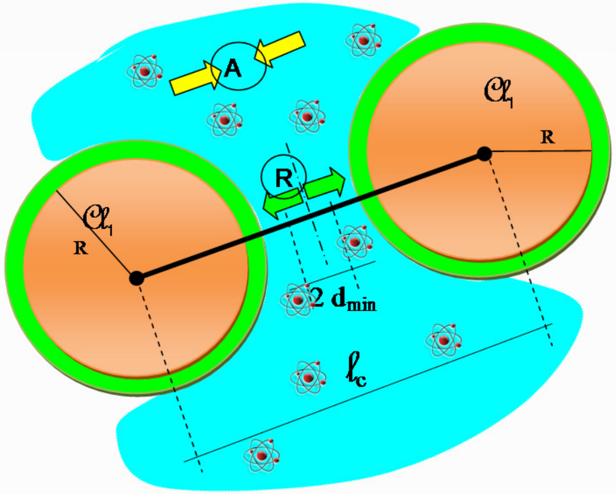
2 Parameters:

l_0: l_c at liquid limit

R_0: mean radius of the clusters (SEM photoanalyses)

Micromechanical approach

Under isotropic loading conditions



$\tilde{B}$, $\tilde{A}$ and $d_{\min}$

Identify from macro experimental data

Microrelation and local parameters

$$f_i^{\alpha} = f^{\alpha}(\delta_i^{\alpha})$$

Potential expressions

Van der Waals (1873), Gouy (1910), Chapman (1913)
Hamaker (1937), Verwey and Overbeek (1948)

Total potential in cluster/water/cluster

$$\begin{cases} w_R = \tilde{B}\ \mathrm{R}\ e^{-d_{\min}^{-1}(l_c-2R)} \\ w_A = -\tilde{A}_w\left[\dfrac{2R^2}{l_c^2-4R^2}+\dfrac{2R^2}{l_c^2}+\ln\left(\dfrac{l_c^2-4R^2}{l_c^2}\right)\right] \end{cases}$$

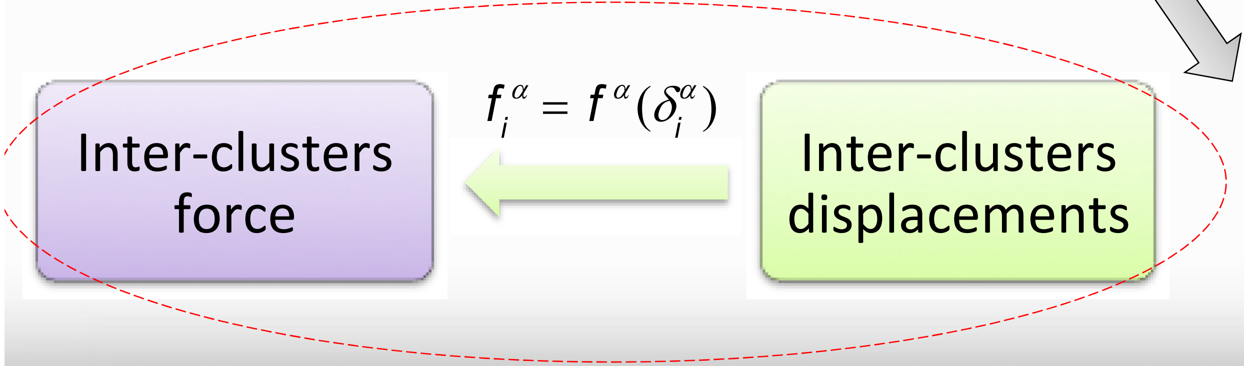
$$w = w_R + w_A$$

Forces deduced by derivation of w

$$f = -\tilde{B}\mathrm{R}\ \mathrm{d}_{\min}^{-1}\ e^{-d_{\min}^{-1}(l_c-2R)} + \tilde{A}R^2\left[\frac{l_c}{\left(l_c^2-4R^2\right)^2}+\frac{1}{l_c^3}-\frac{2}{l_c\left(l_c^2-4R^2\right)}\right]$$

Repulsive part

Attractive part



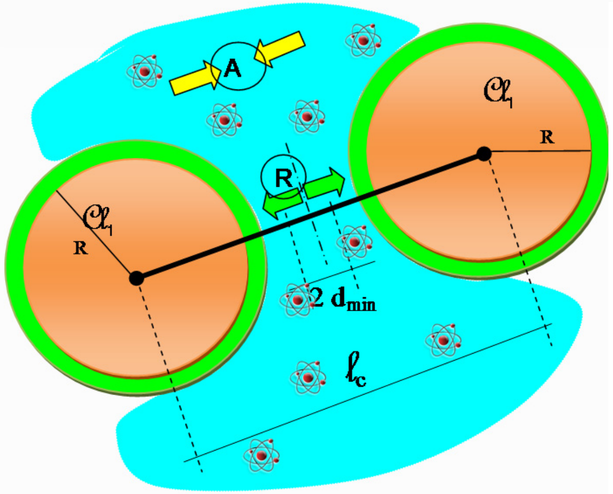
Inter-clusters force

$$f_i^{\alpha} = f^{\alpha}(\delta_i^{\alpha})$$

Inter-clusters displacements

Micromechanical approach

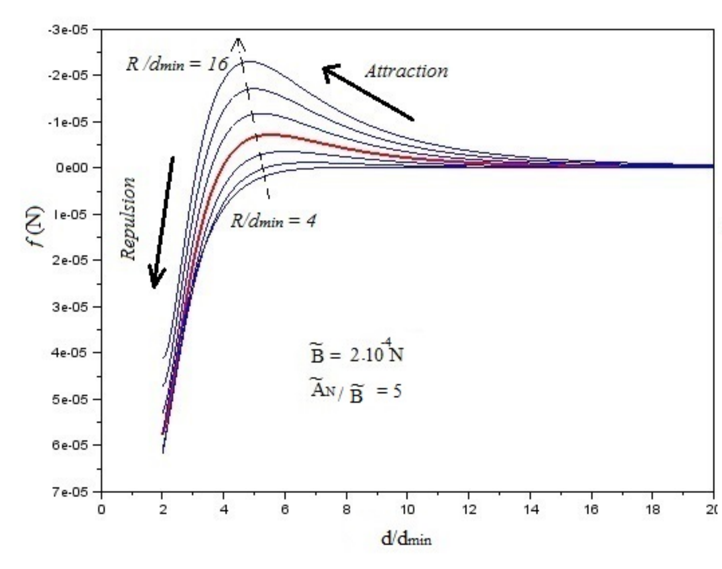
Under isotropic loading conditions

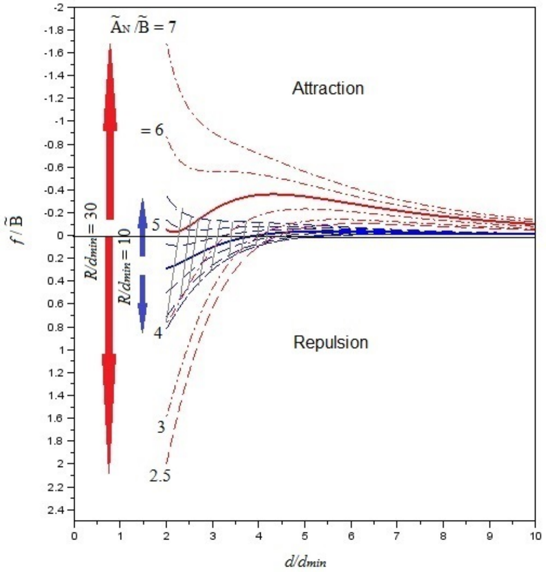


$\tilde{B}$, $\tilde{A}$ and d_{min}

Identify from macro experimental data

Microrelation and local parameters





$$f = -\boxed{\tilde{B}}\, R\, \boxed{d_{\min}^{-1}}\, e^{-d_{\min}^{-1}(l_c - 2R)} + \boxed{\tilde{A}} R^2 \left[\frac{l_c}{\left(l_c^2 - 4R^2\right)^2} + \frac{1}{l_c^3} - \frac{2}{l_c\left(l_c^2 - 4R^2\right)} \right]$$

Repulsive part

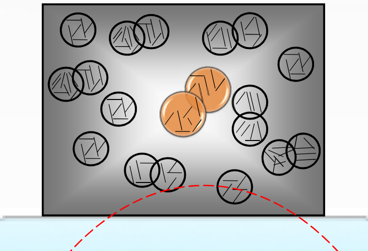
Attractive part

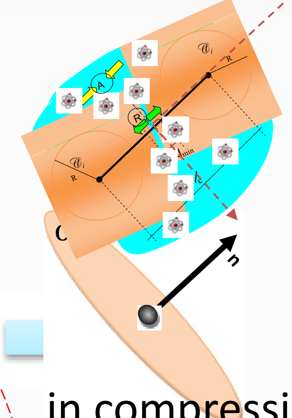
Inter-clusters force

$f_i^{\alpha} = f^{\alpha}(\delta_i^{\alpha})$ ←

Inter-clusters displacements

Micromechanical approach





Stress

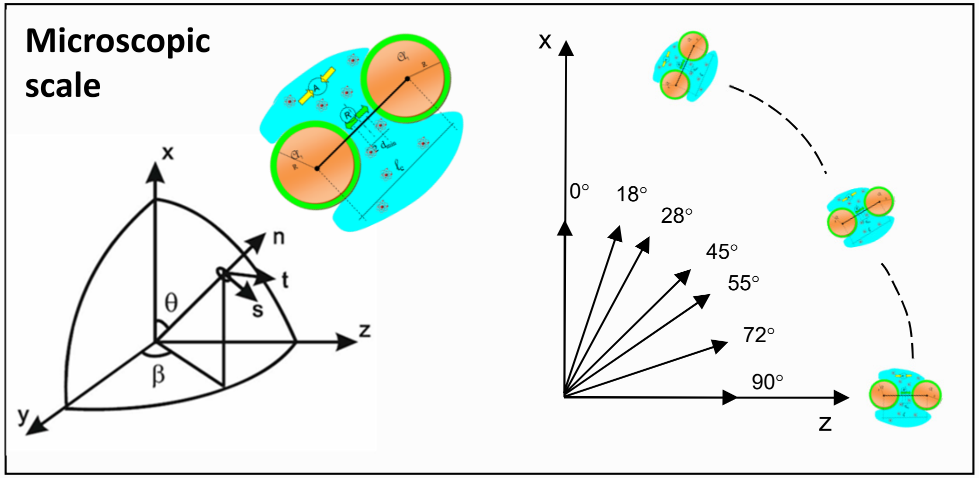
in compression

$$\sigma_{ij} = \frac{1}{V}\sum_{\alpha=1}^{N_c} f_j^{\alpha} l_i^{\alpha}$$

Inter-clusters force

Micromechanical modeling by CHANG (1988), Chang and Liao (1994) – Chang and Hicher (2005)

Micro-Macro Transition



$$\sigma_{ij} = \frac{1}{V}\sum_{\alpha=1}^{N_c} f_j^{\alpha} l_i^{\alpha}$$

Christofferson et al. (1981), Rothenburg and Selvadurai (1981)

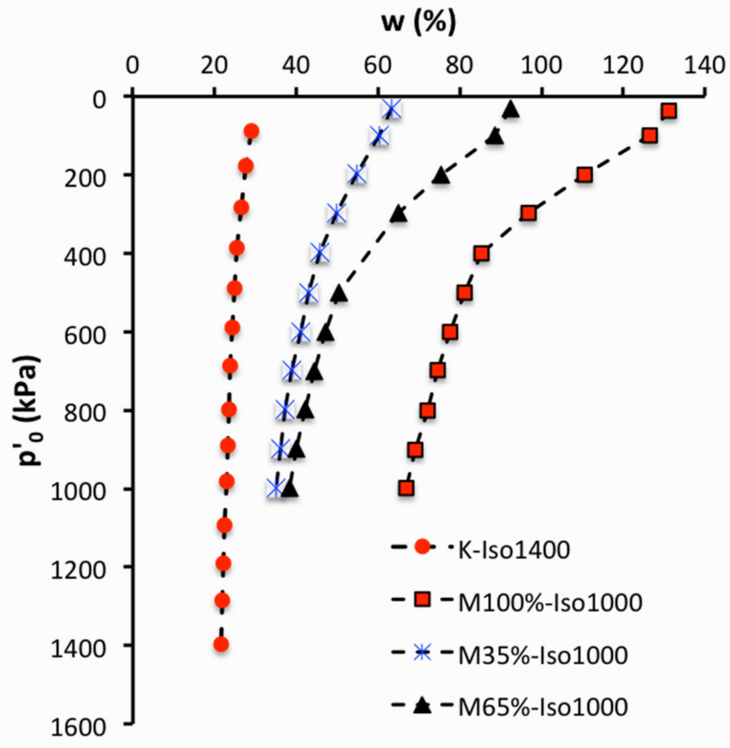
$$N_c/V = 12\Big/\left((\pi/3)(2R)^3(1+e)\right)$$

$$l_c = 2R_0\sqrt[3]{(1+e)/(1+0.35)}$$

Under isotropic loading conditions

$$\sigma_m = \frac{f\ l_c N_c}{V}$$

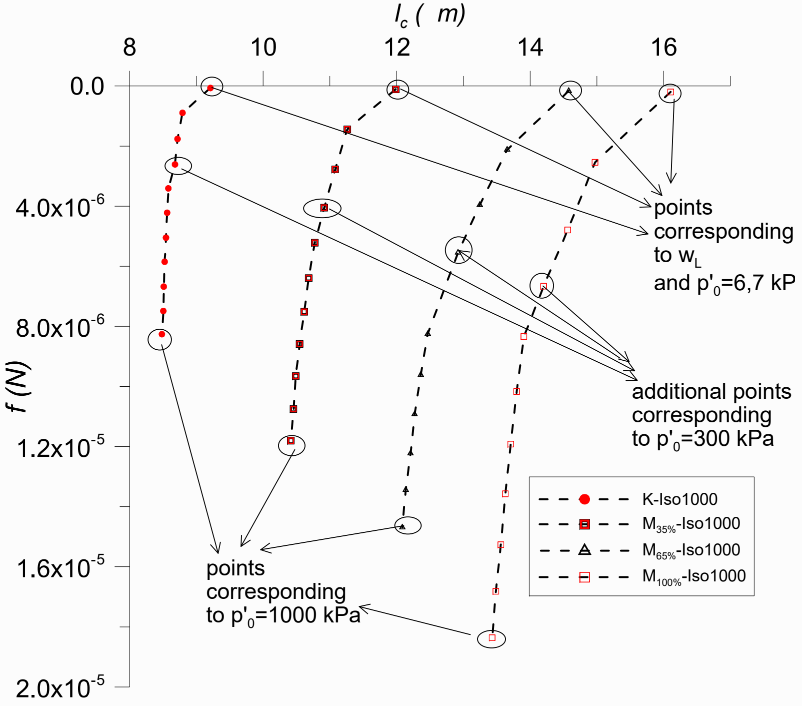
Micromechanical approach



$$\sigma_m = \frac{f\ l_c N_c}{V}$$

$$l_c = 2R_0\sqrt[3]{(1+e)/(1+0.35)}$$

Local f-l_c relationship

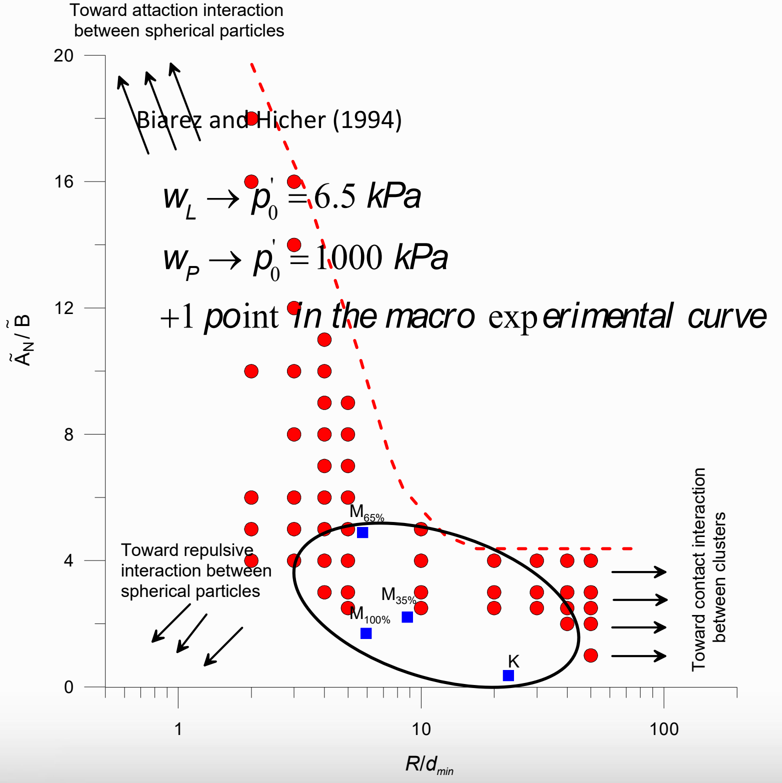


Local equation resolution for the three particular points

$\tilde{B}$, $\tilde{A}$ and $d_{\min}$

Identify from macro experimental data

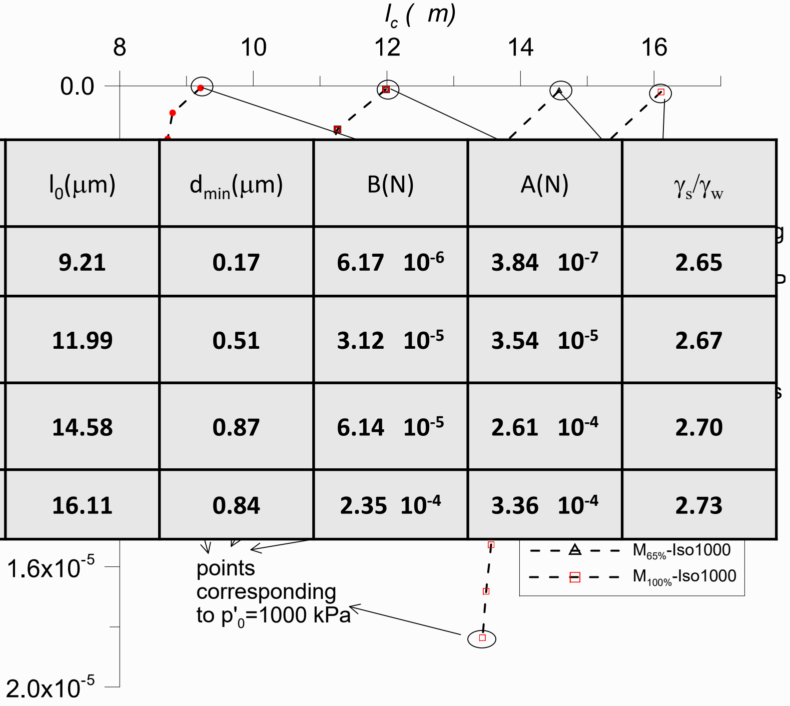
$$f = -\tilde{B}R\, d_{\min}^{-1}\, e^{-d_{\min}^{-1}(l_c-2R)} + \tilde{A}R^2\left[\frac{l_c}{\left(l_c^2-4R^2\right)^2}+\frac{1}{l_c^3}-\frac{2}{l_c\left(l_c^2-4R^2\right)}\right]$$



$w_L \rightarrow p'_0 = 6.5\ kPa$

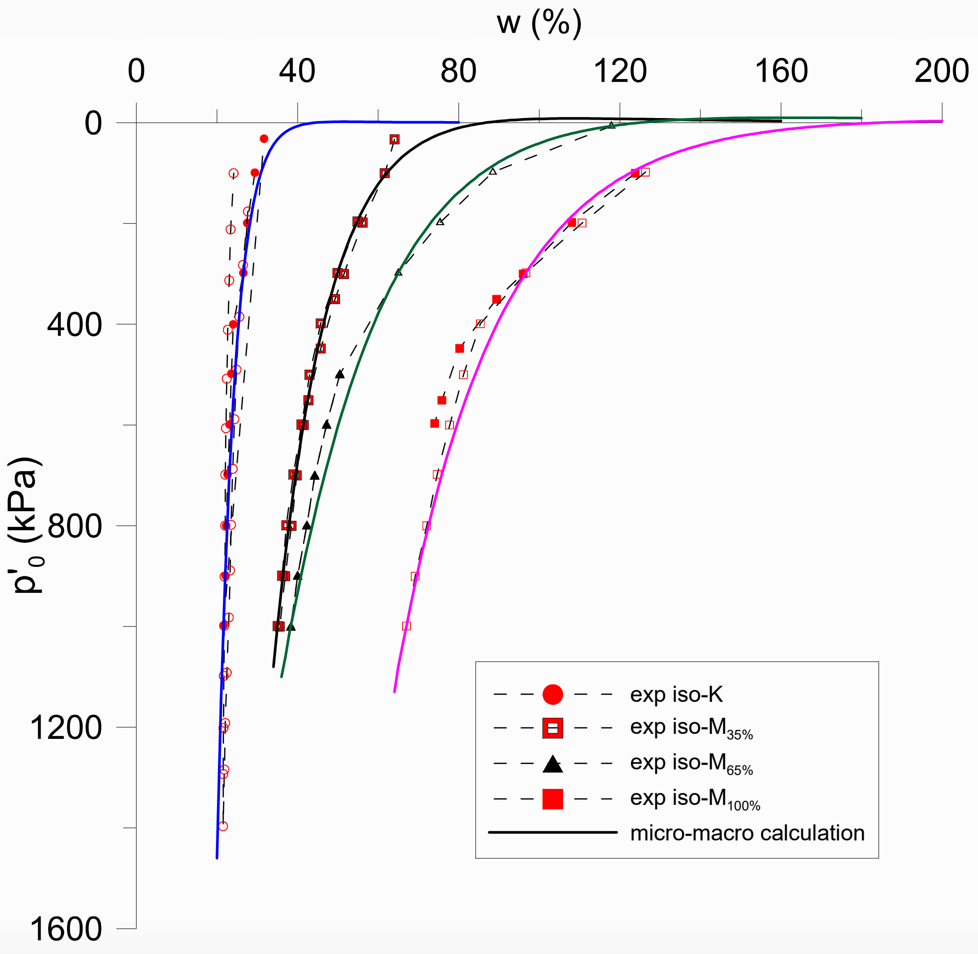
$w_P \rightarrow p'_0 = 1000\ kPa$

$+1$ point in the macro experimental curve



Material	R_0 (μm)	l_0(μm)	d_{min}(μm)	B(N)	A(N)	γ_s/γ_w
K	4	9.21	0.17	$6.17\ 10^{-6}$	$3.84\ 10^{-7}$	2.65
$M_{35\%}$	4.5	11.99	0.51	$3.12\ 10^{-5}$	$3.54\ 10^{-5}$	2.67
$M_{65\%}$	5	14.58	0.87	$6.14\ 10^{-5}$	$2.61\ 10^{-4}$	2.70
$M_{100\%}$	5	16.11	0.84	$2.35\ 10^{-4}$	$3.36\ 10^{-4}$	2.73

Simulation results and comparison with experimental results



Partie 2 –Conclusions

1 **Encouraging results are obtained showing good agreement between experimental results and simulations, highlighting clearly the variation of the behavior related to the montmorillonite fraction variation on isotropic path**

2 **Micromechanical Chang modelling appears as as quite relevant to consider Physical-Chemical aspects in the clay behavior**

3 Physical Chemical aspects between clusters are taken into account through repulsive and attractive forces similar to double layers and van deer Waals forces

4 Parameters choice for the local law permit to estimate these forces between clusters in the case of a mix kaolinite/montmorillonite clay, whose the variation of mineralogy and physical properties are caused by the percentage variation of montmorillonite fraction.