UMR RECOVER

Investigation of Soil **Microstructural Changes** Induced by Suffusion using X-Ray Computed Tomography Technique

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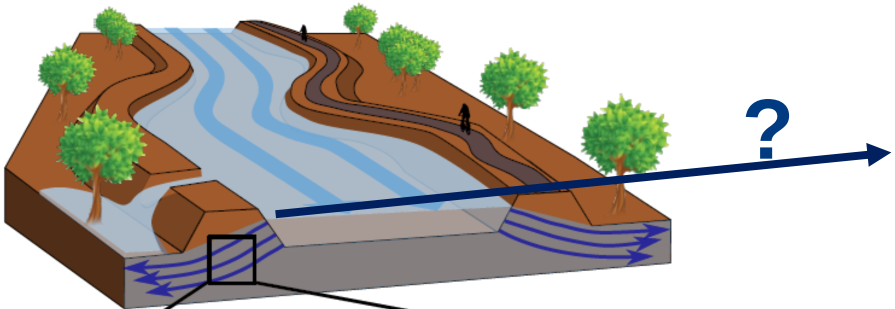
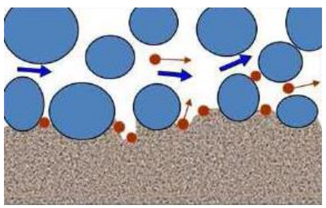
Context: Erosion/Stability of hydraulic structures



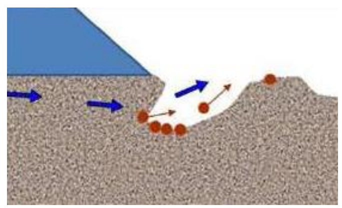
(11 victimes, 2G$)

- France: 1 Failure/year → 100 M€/y
- 46% due to internal erosion

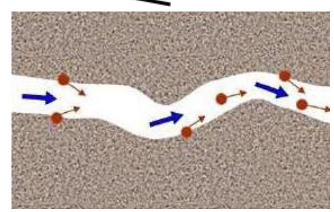
4 types of internal erosion



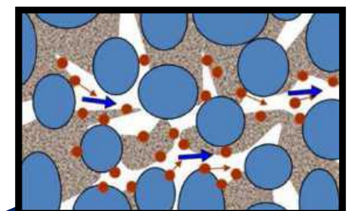
Contact erosion



Backward erosion

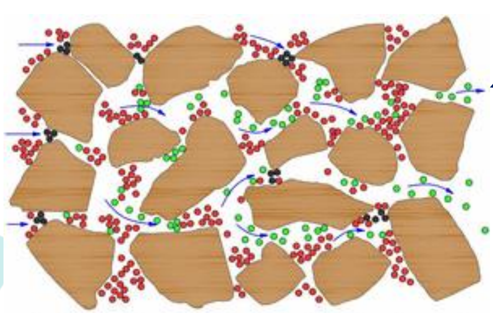


Concentrated leak



Suffusion

- **Suffusion :** detachment and migration of the finest soil particles within the surrounding soil skeleton formed mainly of large grains under seepage flow



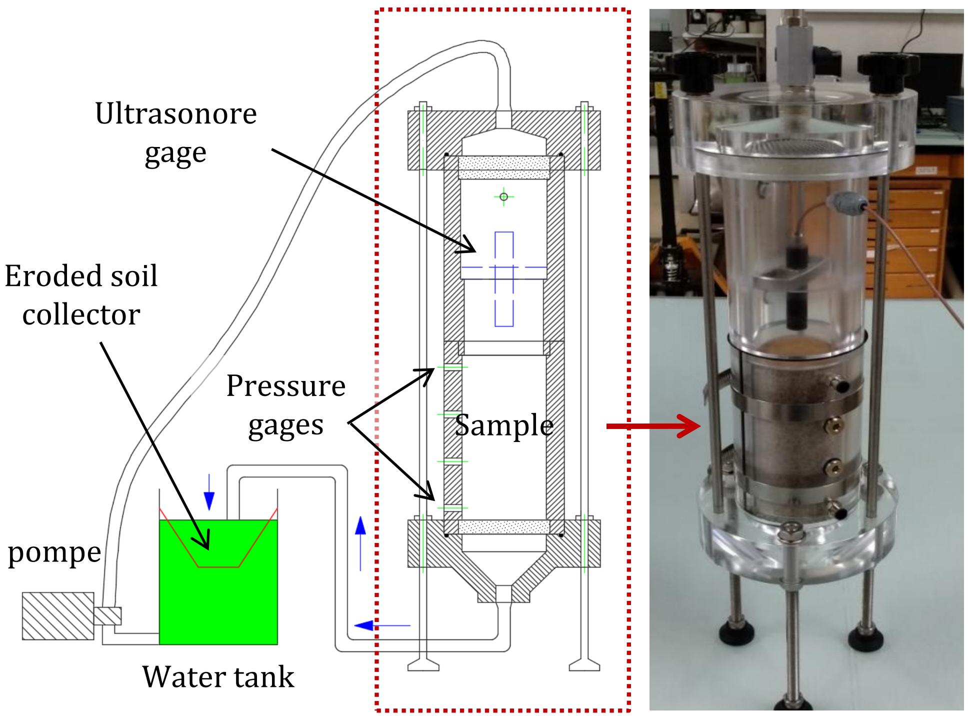
● Fines ● Detached fines ● Blocked fines

Consequences :

- Increase of porosity
- Settlement
- Change of the microstructure ?
- Impact on mechanical behavior ?
- etc…

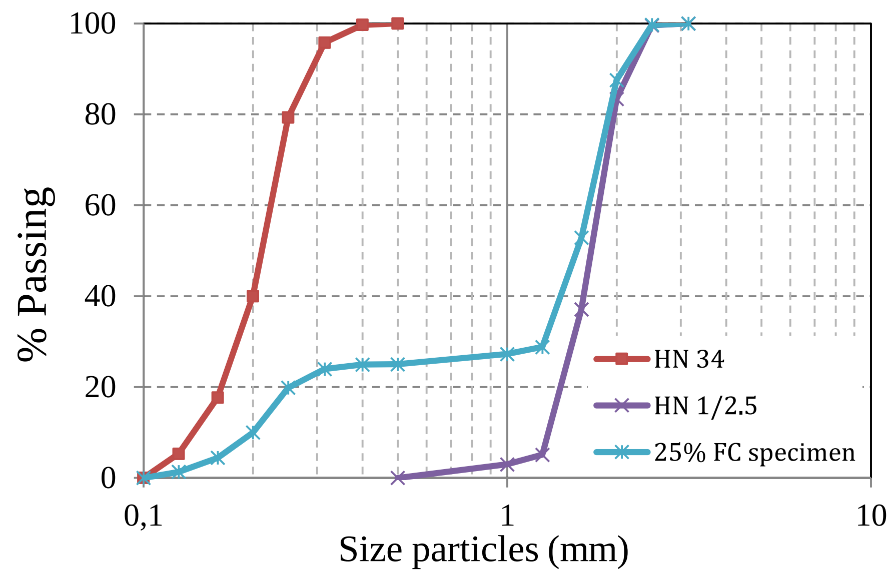
Experimental method

Suffusion permeameter (SEPT)



Tested materials

- Binary mixture of Hostun silica sand
- Fine content $FC = 25\%$
- Relative density $D_r = 40\%$



Test :

- Controlled downward flow
- Closed system
- Sample : ϕ=7 cm, H= 14 cm

Measured parameters:

- Hydraulic pressure
- Eroded mass
- Settlement

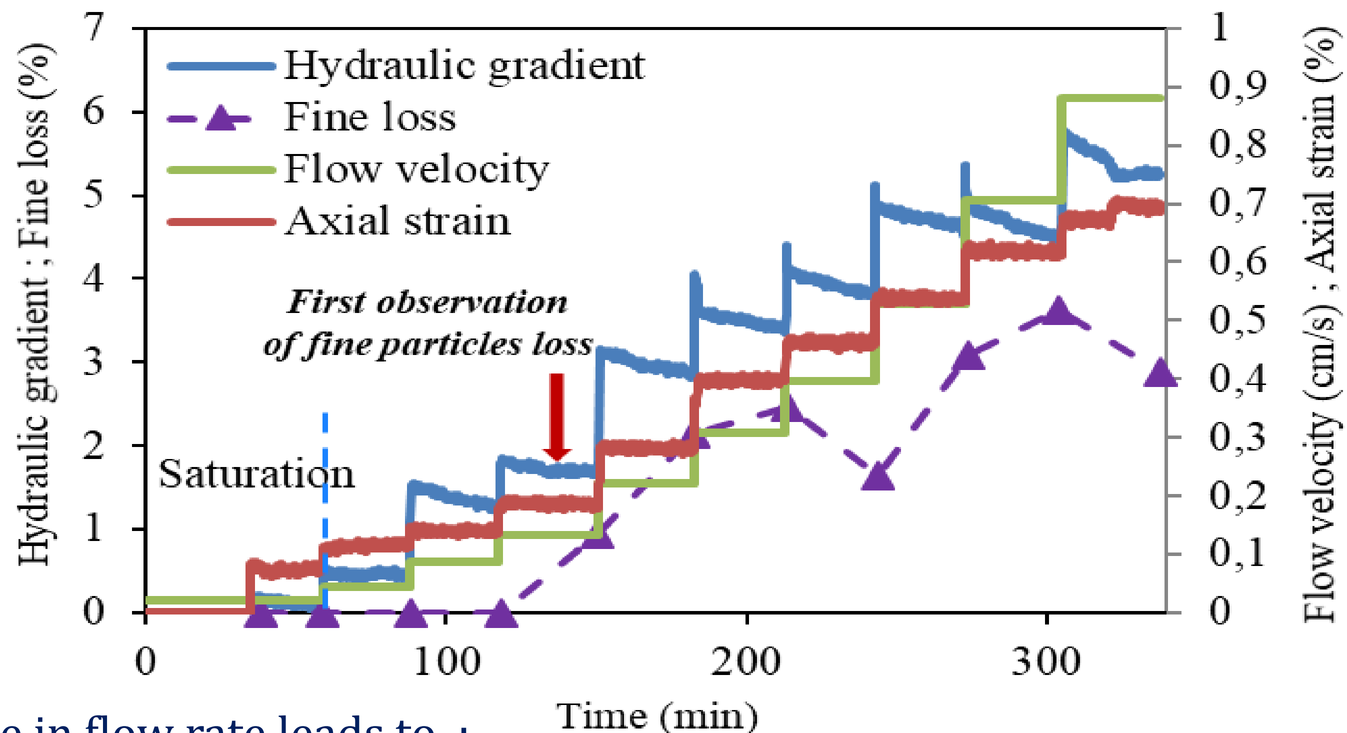
Fines
HN 34 (0,1/0,4 mm)

Coarse grains
HN 1/2,5 mm

Eroded soil behavior at macroscopic scale

Procedure and typical results of the suffusion test :

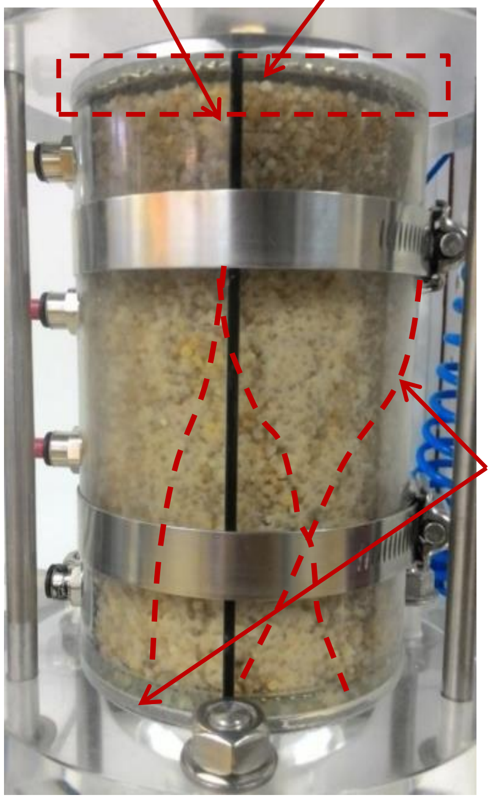
- Saturation: upward flow at low rate
- Suffusion test: downward seepage by successive velocity steps



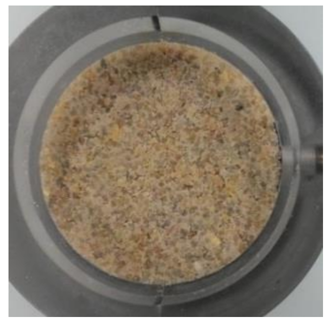
- Increase in flow rate leads to :
  - Increase in hydraulic gradient
  - Occurrence of settlements instantaneously
  - A strong washout of fines at each new flow velocity step

Eroded soil behavior at macroscopic scale

Visual observations of the erosion process :



$v = 0{,}3 \text{cm/s}$ $v = 0{,}7 \text{cm/s}$



Initial state

Erosion zone

Spreed of the erosion zone

- Local initiation of the erosion at certain points and then progression along preferential paths in a large area

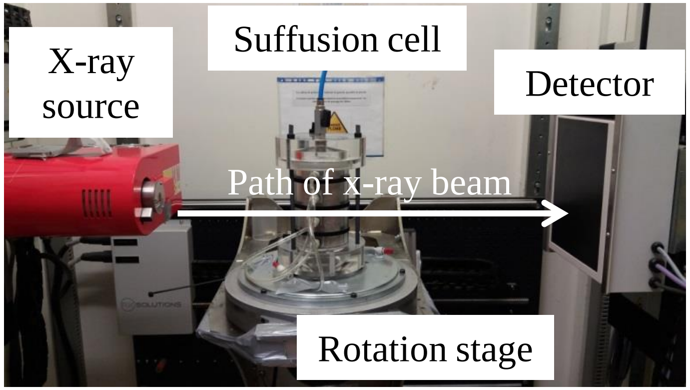
➢ **Occurrence of heterogeneities** observed from the side of the cell : How about **inside the sample ?**

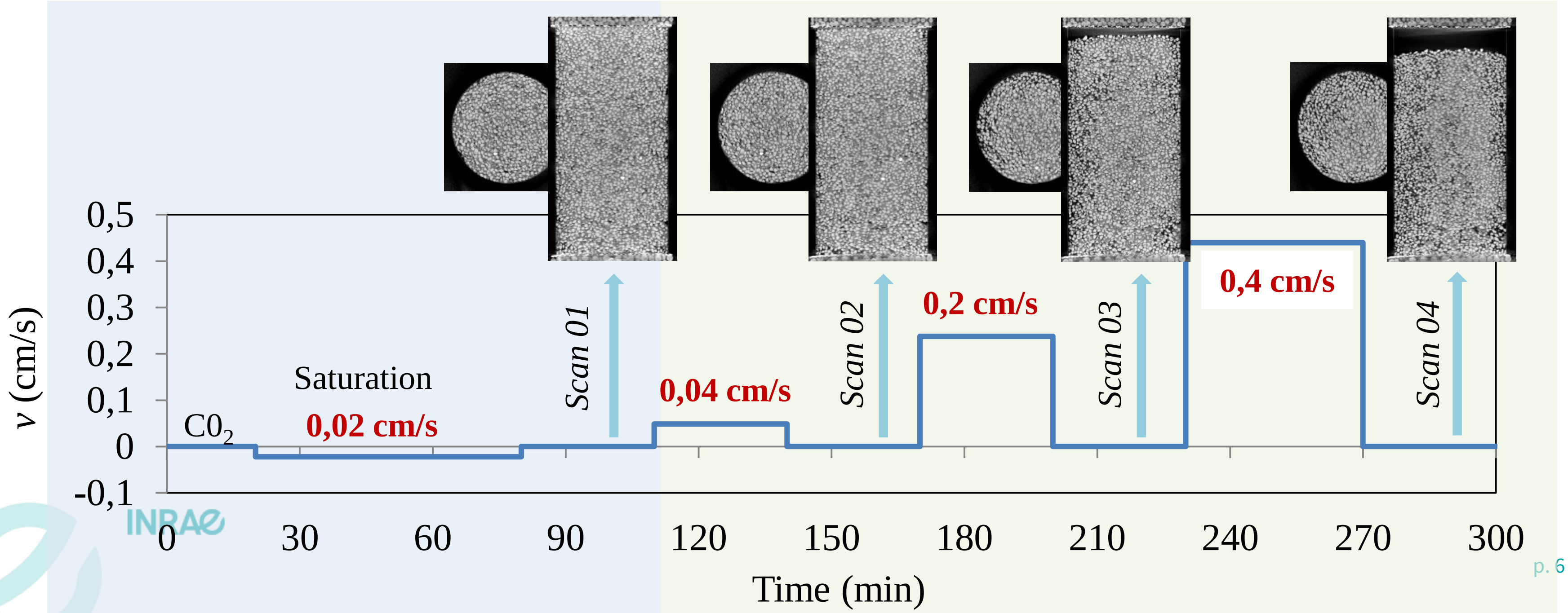
Eroded soil behavior at microscopic scale

X-ray tomography investigations :

- Specimen: **7 cm** diameter, **14 cm** height
- $FC = 25\%$; $D_r = 40\%$
- Erosion test: downward flow
- Spatial resolution: 90 µm/px

Laboratoire 3SR

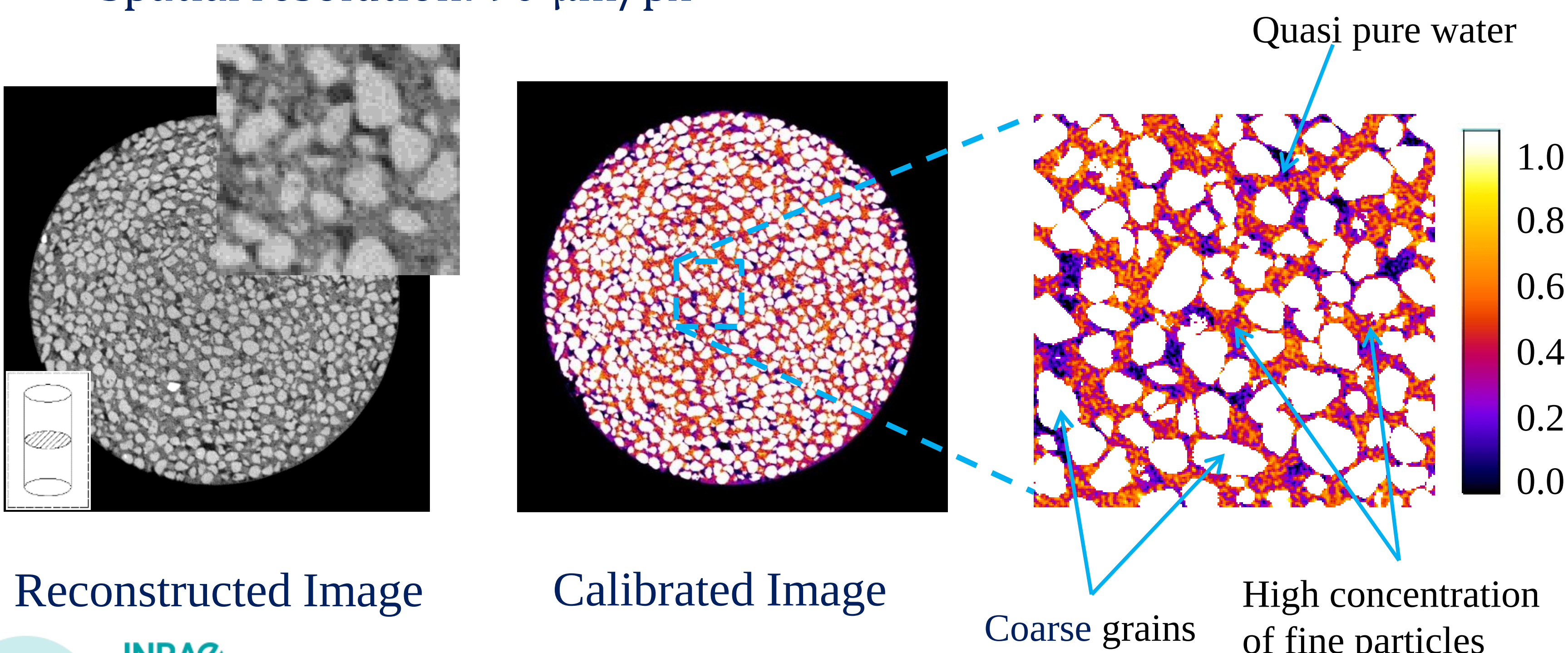




Eroded soil behavior at microscopic scale

Image processing :

- Identification of coarse grains
- Grey scale calibration: determination of the fine particles fraction in the inter-granular spaces
- Spatial resolution: 90 µm/px

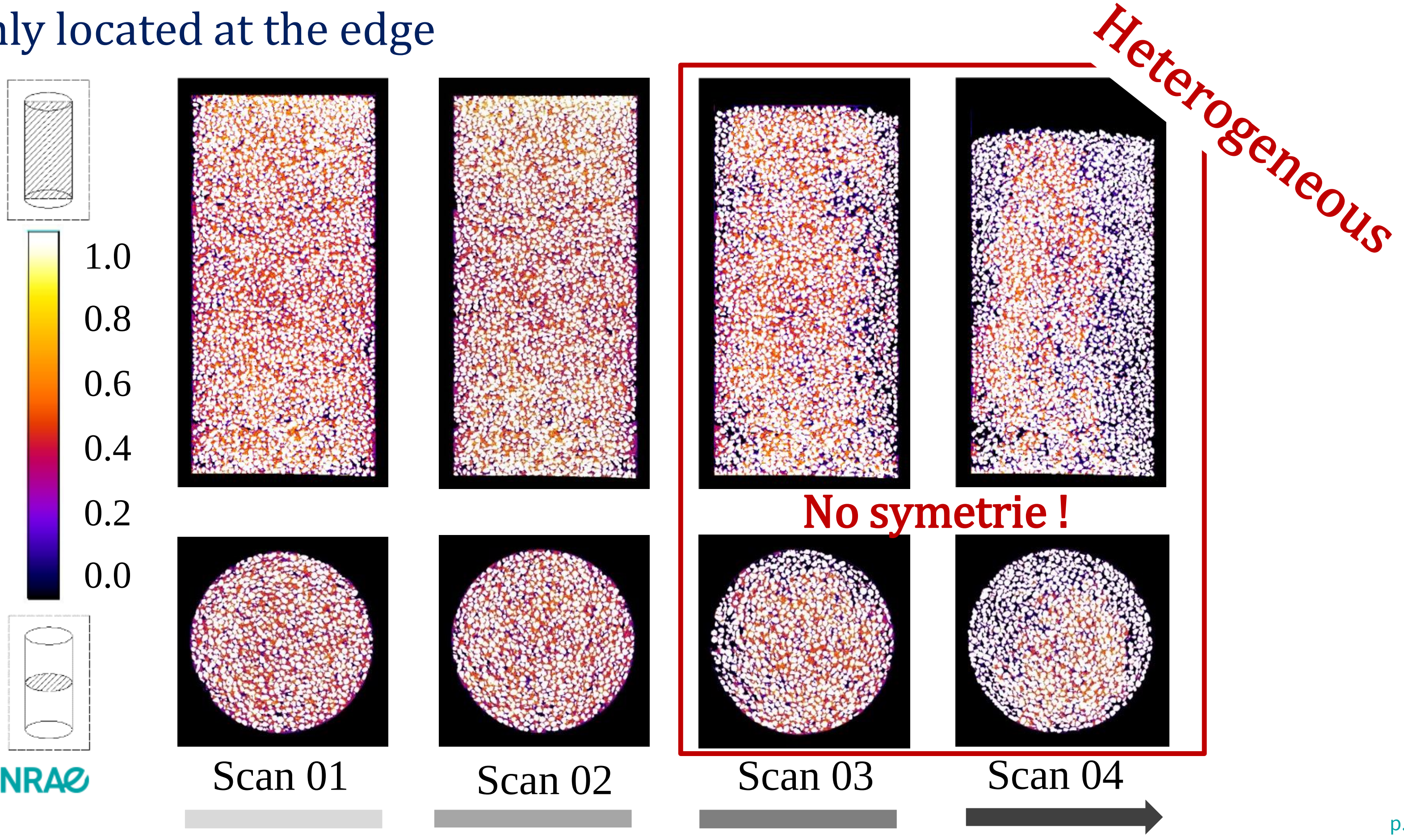


Nguyen C.D., Benahmed N., Andò E., Sibille L., Philippe P. *Experimental investigation of micro-structural changes of soils eroded by suffusion using x-ray tomography,* (Acta Geotechnica, 2019).

Eroded soil behavior at microscopic scale

Fine particles distribution

- Before erosion: homogeneous spatial distribution of fines
- After erosion → occurrence of heterogeneities : fine particles removal mainly located at the edge



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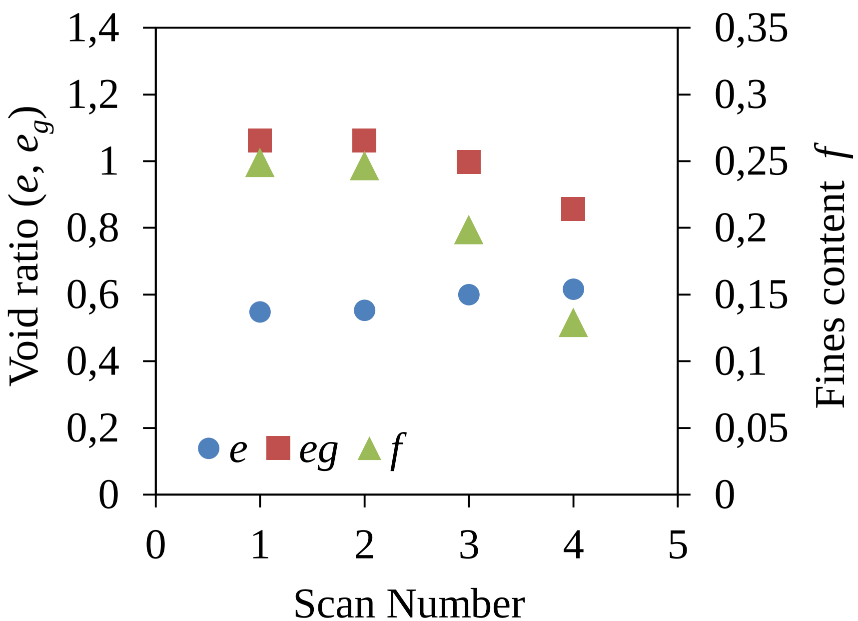
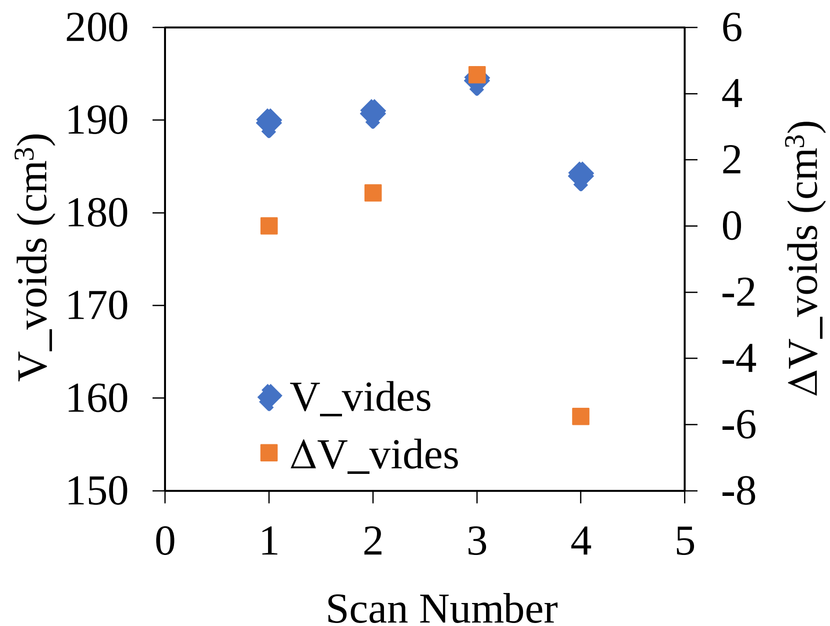
Eroded soil behavior at microscopic scale

Analysis at sample scale

- Diminution of f → increase of e and decrease of e_g
- Variation of volume of voids : competition between the fines loss and the sttelment of the granular skeleton





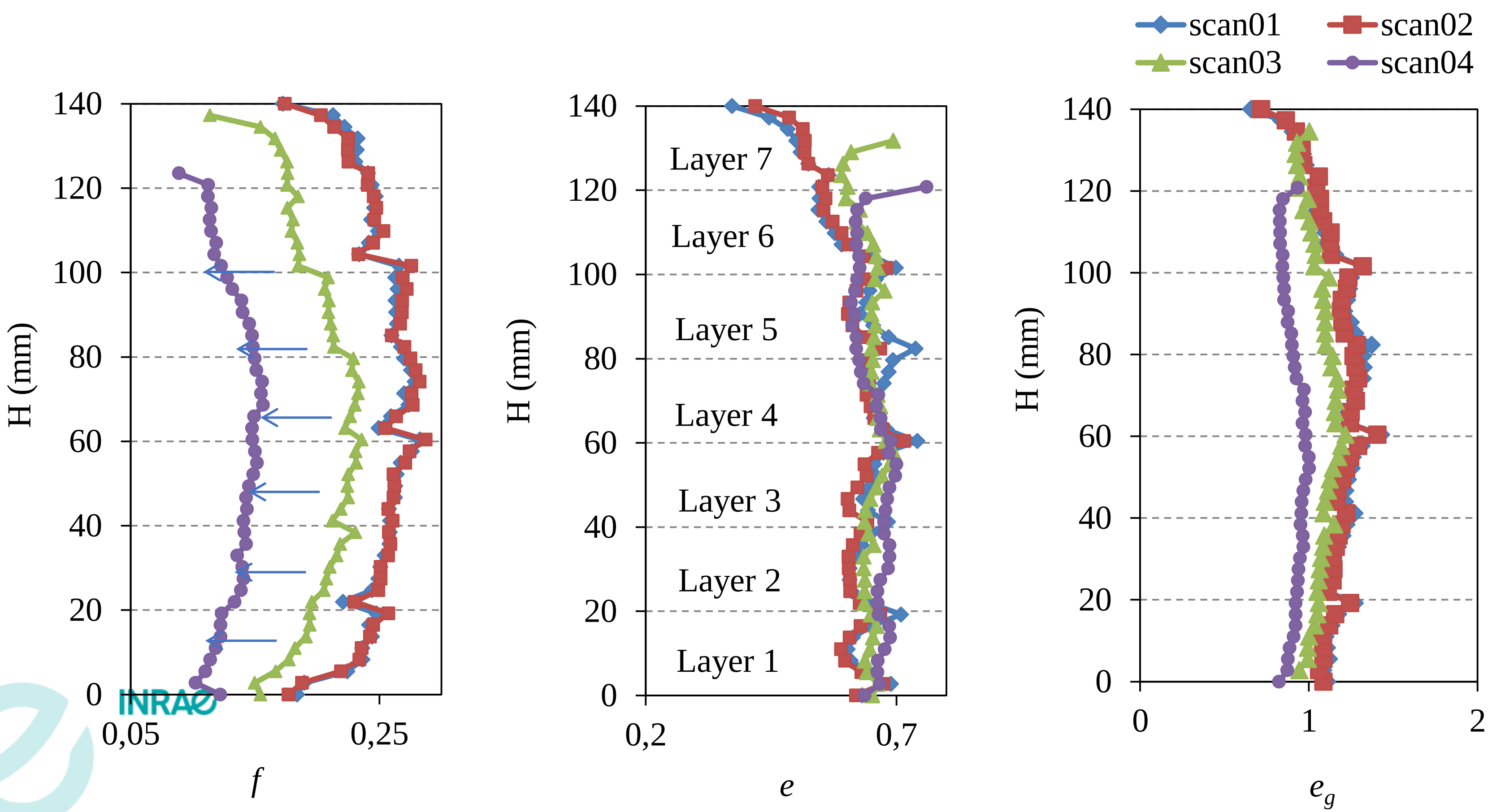
Variation of volume of voids

INRAE

Eroded soil behavior at microscopic scale

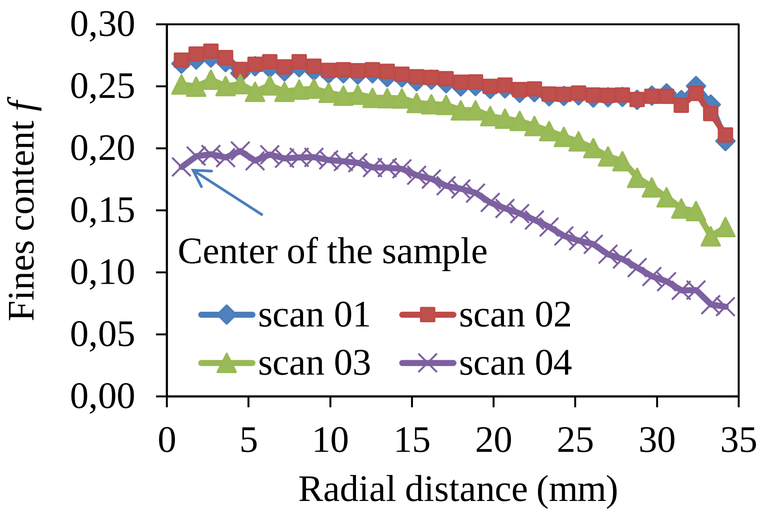
Vertical profils

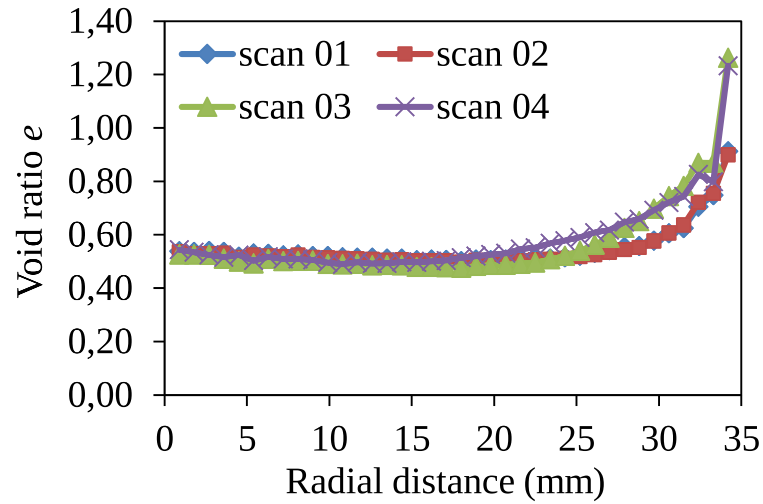
- A sligth signature of the sample preparation method by moist tamping
- *Fines content(f)*, void ratio (e), inter-grains void ratio (e_g): fairly homogeneous after erosion processus

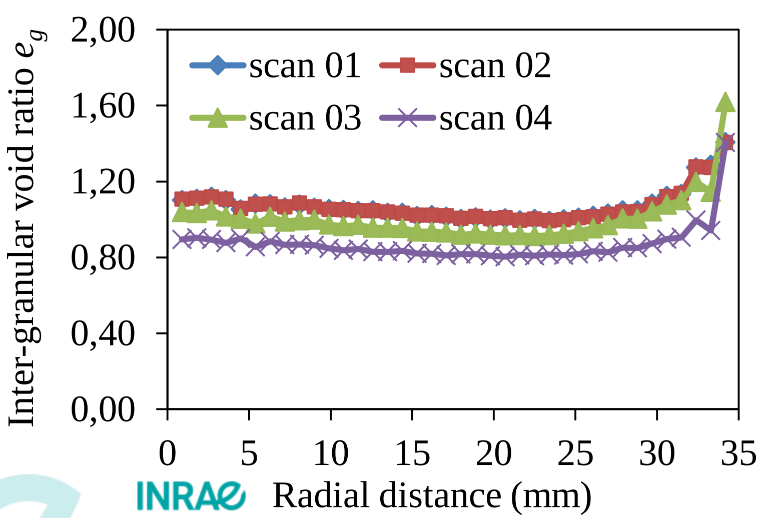


Eroded soil behavior at microscopic scale

Radial profiles of physical properties







→ erosion of fines is strongly heterogeneous

- Edge effect → strong heterogeneity
- *f* :Hight fines loss at boundarie
- *e* : varies only at boundarie
- e_g : global compaction

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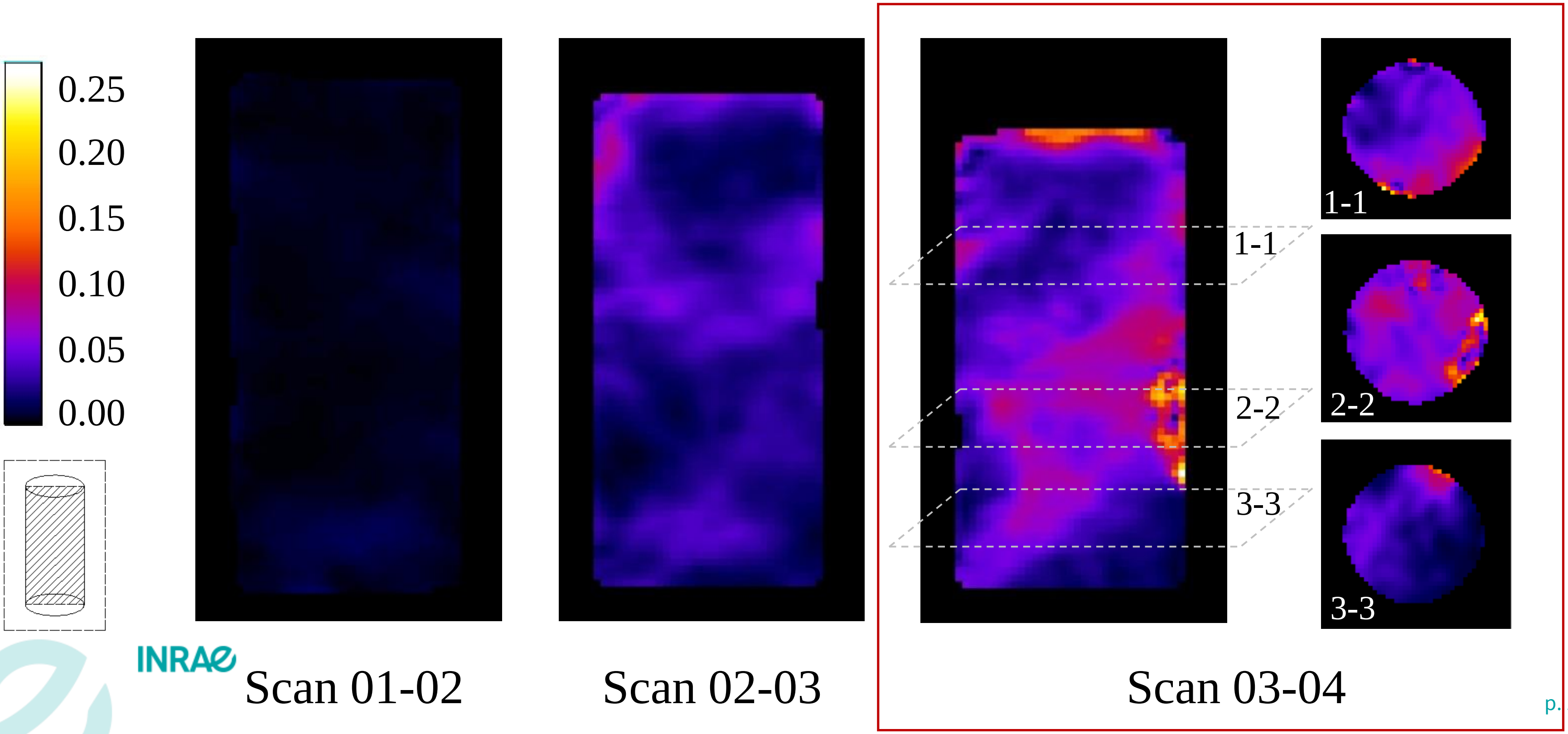
Physical properties are averaged at a radial distances from the revolution axis of the sample in the volume between (r – Δr/2) and (r + Δr/2) → f(r), e(r), and e_g(r)

Eroded soil behavior at microscopic scale

Deformation fields: Incremental deviatoric strain

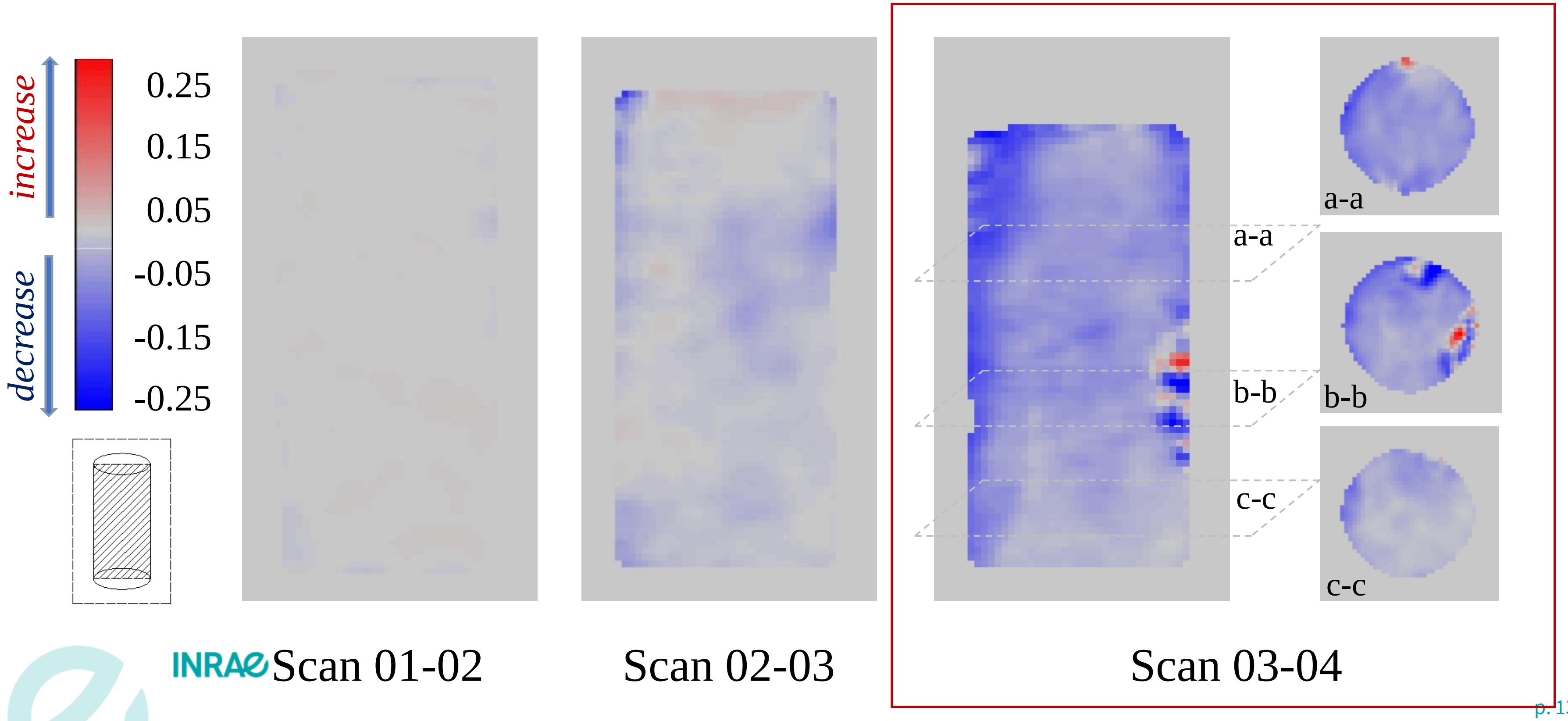
- **Presence of shear strains** in the bulk of the sample du to the heterogeneity of the suffusion process development, with high shear intensity near the sample boundaries



Eroded soil behavior at microscopic scale

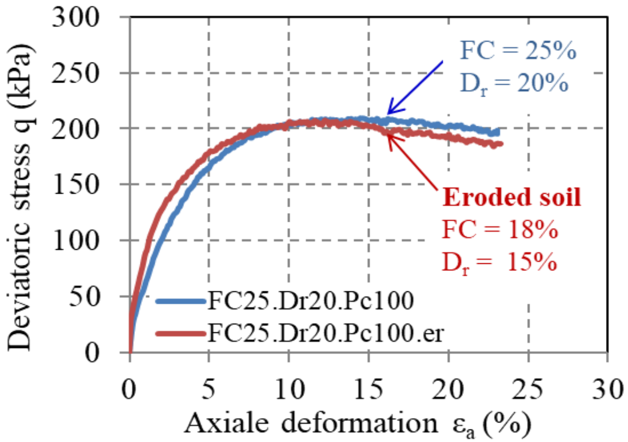
Deformation fields: Incremental volumetric strain

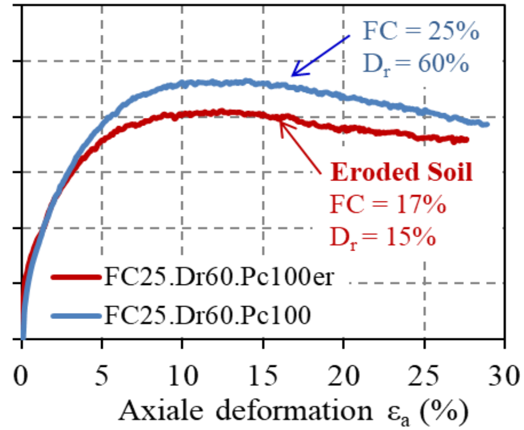
- **Presence** of a **non uniform volume deformation fields** caused by differential settlement : significant volume decrease occurs at the sample boundaries !



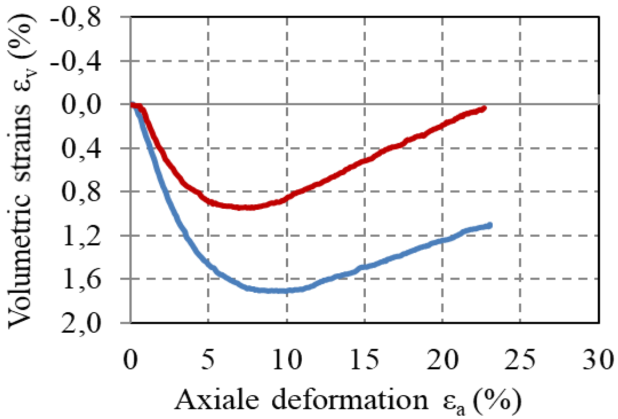
Eroded soil behavior at macroscopic scale

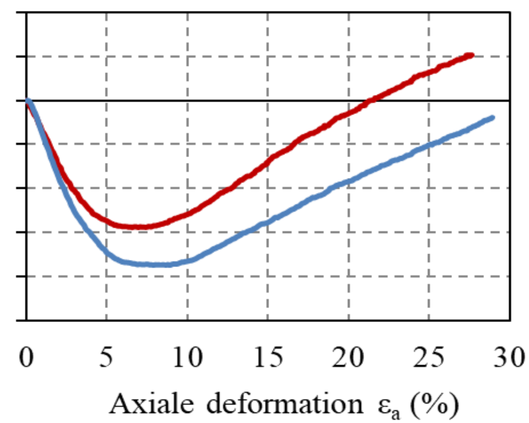
Mechanical behavior : Drained triaxial tests on non-eroded and eroded soils





Post suffusion frozen sample





Sample ready for triaxial test

- No (or small) decrease in the peak shear stress
- No consistency between volumetric strains and déviatoric stress !!!

(Nguyen 2018)

CONCLUSION

➔ Suffusion process is highly **heterogeneous**

- Existence of preferential flow paths
- Enhanced variation of fines content and void ratio at the periphery;
- Global compaction of the coarser granular skeleton (settlement)
- Appearance of shear strains in the sample
- Appearance of non-uniform volumetric strain field

The effect of soil microstructure has to be taken into account in the mechanical behavior analyses of eroded soils.

Thank you for your attention !

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Nguyen C.D., Benahmed N., Andò E., Sibille L., Philippe P. (2019). *Experimental investigation of micro-structural changes in soils eroded by suffusion using X-ray tomography*. Acta Geotechnica. https://doi.org/10.1007/s11440-019-00787-w.

Nguyen C.D., Benahmed N., Philippe P., Andò E., Sibille L., (2018). *The effect of suffusion on physical properties and mechanical behavior of granular soils*. 9th International Conference of Scour and Erosion (ICSE), November 5–8, 2018, Taipei, Taiwan.

Aboul Hosn R., Benahmed N., Nguyen C. D., Sibille L. Chareyre B., Philippe P. (2018). *Effects of Suffusion on the Soil's Mechanical Behavior: Experimental Investigations*. 26th Annual Meeting of European Working Group on Internal Erosion EWG-EI, 10-13 September 2018, Milano, Italy.

Aboul Hosn R., Nguyen C. D., Sibille L., Benahmed N., & Chareyre B. (2017). *Microscale analysis of the effect of suffusion on soil mechanical properties*. 11th International Workshop on Bifurcation and Degradation in Geomaterials (IWBDG 2017), May 21-25, 2017, Limassol, Cyprus.

Nguyen, C. D., Benahmed, N., Philippe, P., and Diaz Gonzalez, E. V. (2017). *Experimental study of erosion by suffusion at the micro-macro scale*. 8th International Conference on Micromechanics of Granular Media (Powders and Grains), 3-7 July 2017, Montpellier, France. EPJ Web of Conferences 140, 09024 (2017).

Mechanical behavior of eroded soil

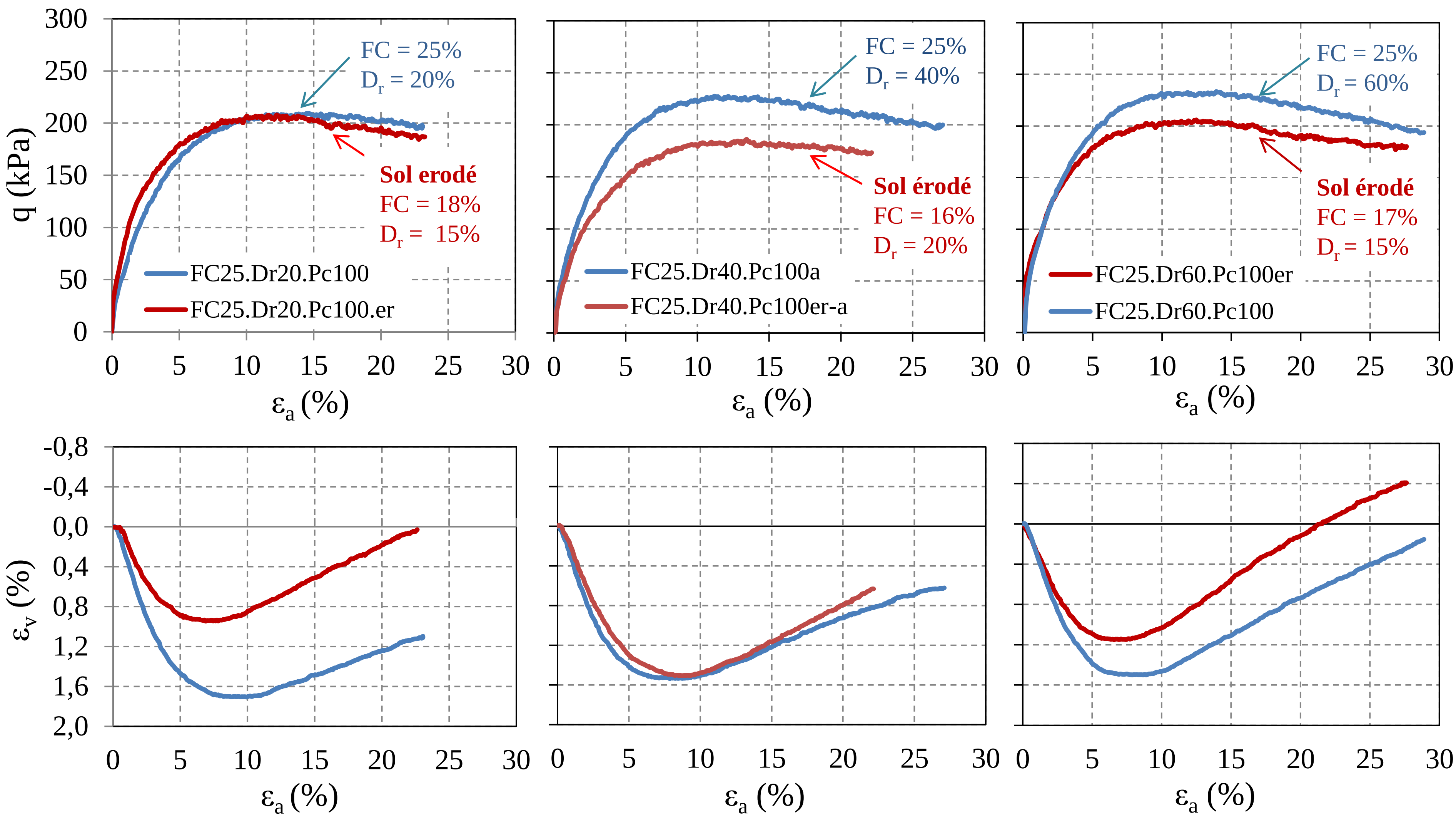
- **Essais triaxiaux sur sol non érodé :** procédure classique
- **Essais triaxiaux sur sol érodé :**
  - Après érosion, désaturation de l'échantillon à $w \approx 6\%$
  - Congélation pendant 16h, démoulage rapide
  - Décongélation (P_c=50kPa) dans la cellule triaxiale avant cisaillement

Désaturation ($w \approx 6\%$)

Congélation & démoulage

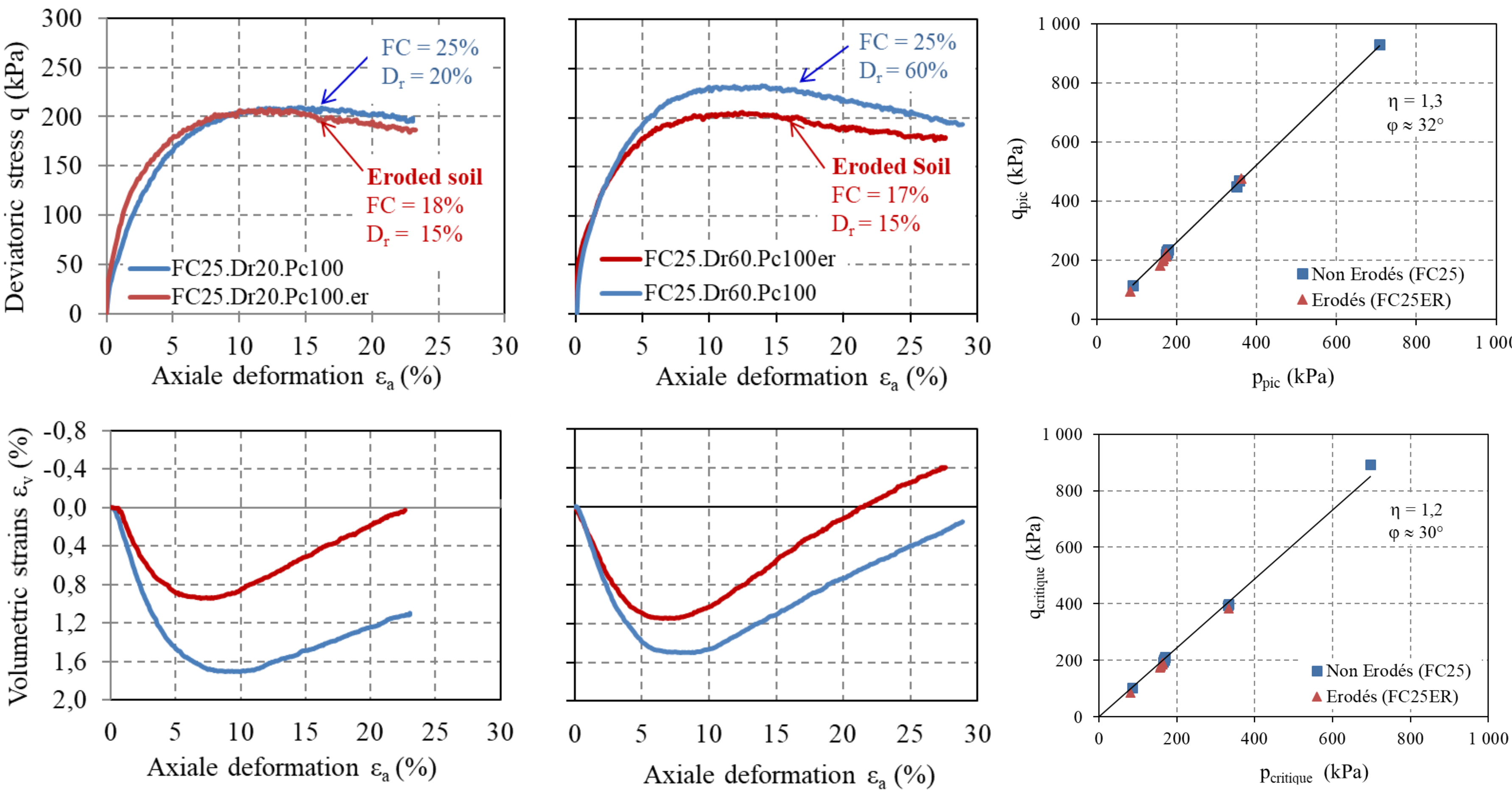
Décongélation

Mechanical behavior of eroded soil



- No or small decrease in the peak shear stress
- Inconsistent volumetric behavior

Mechanical behavior of eroded soil



- No (or small) decrease in the peak shear stress
- Inconsistent volumetric behavior !!!

- No effect on peak and critical friction angle !

Outline

- Introduction
- Experimental method
- Suffusion behavior of soil on a **macroscopic** scale
- Suffusion behavior of soil on a microscopic scale
- Conclusions

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