Numerical modelling of soil suffusion using OpenFOAM

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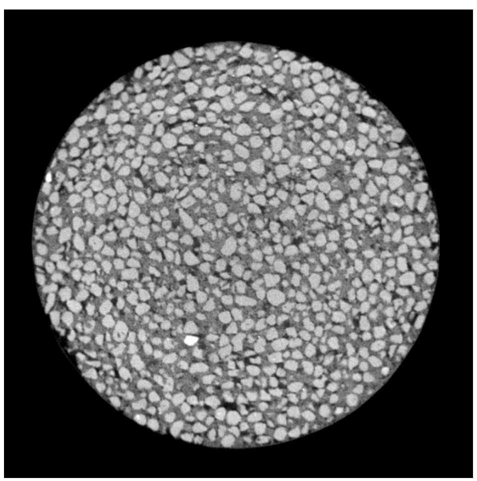


Nguyen et al, 2019

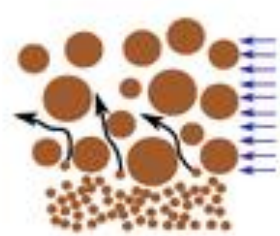
Context and motivation

Erosion / Stability of hydraulic structures

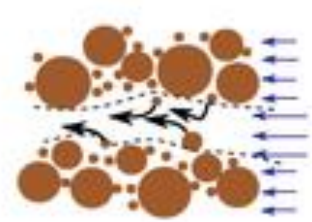
France: **1 dam failure/year**
46% of failures due to internal erosion

4 types of internal erosion

Backward erosion



Contact



Piping

Suffusion

Context and motivation

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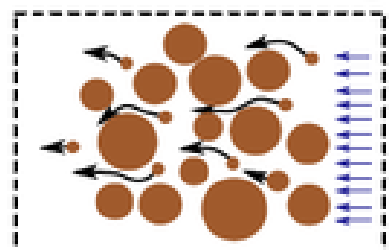
Detachment and migration under seepage flow of the **finest soil particles** within the surrounding soil skeleton formed of **larger grains**



Suffusion

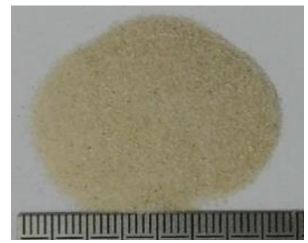
Suffusion permeameter

Input velocity

C.D. Nguyen - Thesis Aix-Marseille (2016-2018)

Binary mixture

Fines content f = 25%



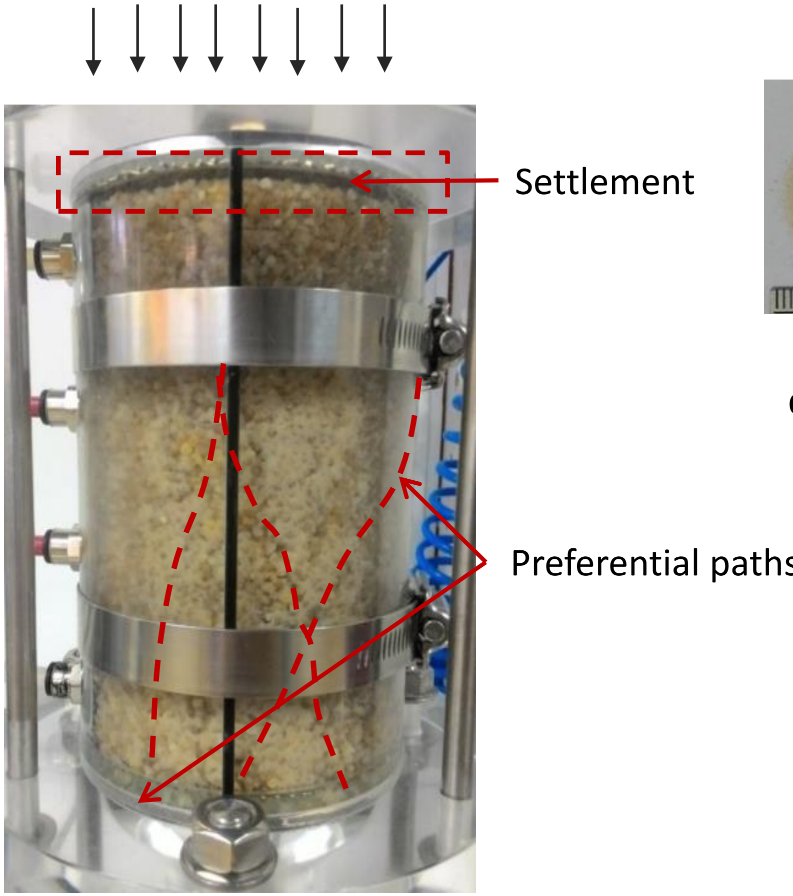
Fines

d_f =0.1/0.4 mm

Coarse grains

d_c= 1/2.5 mm

Suffusion permeameter



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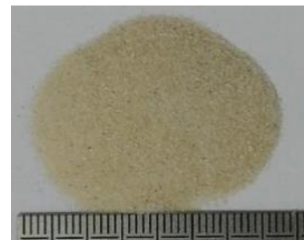


Fines

d_f =0.1/0.4 mm

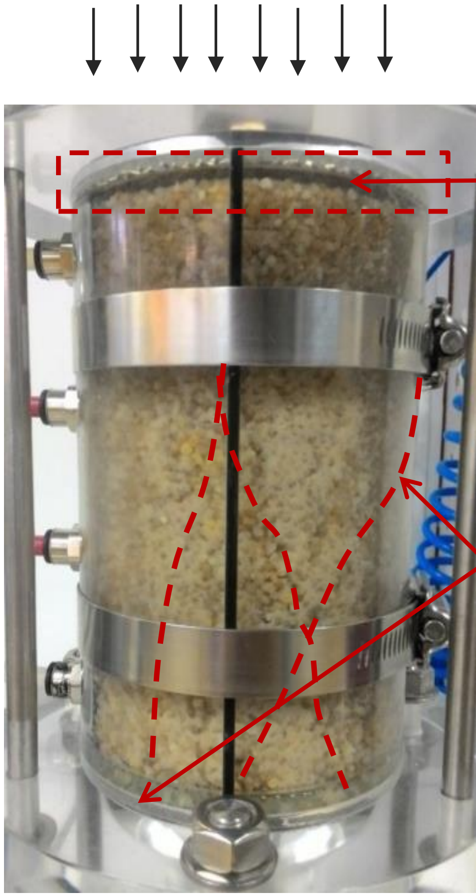
Coarse grains

d_c= 1/2.5 mm

- Increase in porosity
- Settlement
- Preferential paths

Suffusion permeameter

Input veloctiy



Settlement

Preferential paths

C.D. Nguyen - Thesis Aix-Marseille (2016-2018)

Occurrence of heterogeneities during the erosion process

V = 0.3 cm/s

Erosion zone

V = 0.7 cm/s

Expansion of the erosion zone

Internal channelization ?

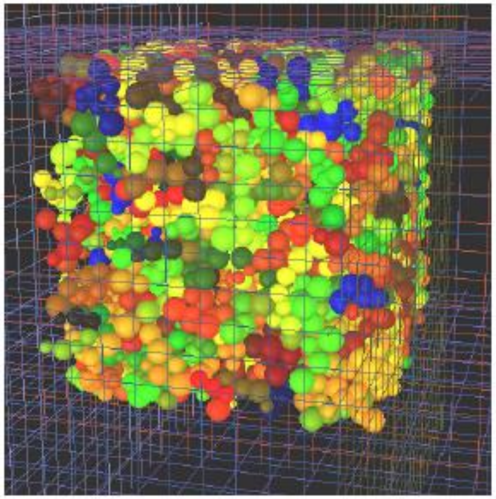
➡ **Numerical modelling**

Numerical modelling

Discrete element approach

Coupling numerical methods that considers:

- Particles (DEM)
- Fluid flow (LBM, PVF...)



(Wautier *et al.* , NAMG 2019)

Continuum approach

Computational fluid dynamics (CFD) that considers:

- Fluid flow through a porous medium
- Erosion process

➡ OpenFOAM

"**Open**-source **F**ield **O**peration **A**nd **M**anipulation"
C++ toolbox involving customized numerical solvers

Model equations for suffusion

Continuity equation $\frac{\partial \rho}{\partial t} + div(\rho\vec{u})=0$

Incompressible fluid $div(\vec{u})=0$

For a porous medium: **Darcy law** $\mathrm{u} = -\frac{k}{\mu}\nabla p$

For a granular material:

Kozeny-Carman $k = C\frac{\rho g}{\mu}\frac{e^3}{1+e}\frac{1}{A^2}$

ρ density

u velocity

p pressure

μ viscosity

k permeability

e void ratio

A specific surface

g gravity

C constant

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To model SUFFUSION mechanism:

- Relationship between **permeability** and grains properties of a **binary mixture** ?
- Equation for the **erosion** process ?

➡ **Local constitutive laws**

Model equations for suffusion

Binary mixture properties

V_f Fine grains volume, d_f diameter, N_f number

V_c Coarse grains volume, d_c diameter, N_c number

Fines content $f = \dfrac{V_f}{V_s}$

Void ratio $e = \left((1-f)\dfrac{V_t}{V_c}\right) - 1$

V_v Void volume

V_s Solid volume

V_t Total volume

Contact surface of the grains $\Sigma = N_f \pi d_f^2 + N_c \pi d_c^2$

Mass balance

$$f V_s = N_f \frac{\pi}{6} d_f^3$$

$$(1-f) V_s = N_c \frac{\pi}{6} d_c^3$$

$$\Sigma = f V_c \frac{6}{d_f} + (1-f) V_s \pi \frac{6}{d_c}$$

Model equations for suffusion

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$$\Sigma = f V_c \frac{6}{d_f} + (1-f) V_s \pi \frac{6}{d_c}$$

$$A = \frac{\Sigma}{V_s}$$

Kozeny-Carman permeability

$$k = C \frac{\rho g}{\mu} \frac{e^3}{1+e} \frac{1}{A^2}$$

Model equations for suffusion

➡ **Local constitutive laws**

f Fines content
e Void ratio

Relationship for the **permeability**

$$k(f) = k(0)\,\frac{e(f)^3}{1+e(f)}\,\frac{1+e(0)}{e(0)^3}\left(\frac{1}{1+\left(\frac{d_c-d_f}{d_f}\right)f}\right)^2$$

Model equations for suffusion

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Local **EROSION** law

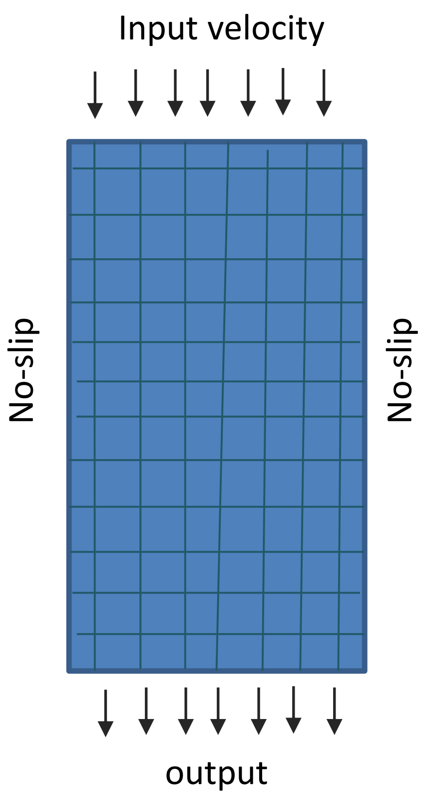
$$\frac{\partial f}{\partial t} = -ef(\|u\| - u_t)$$

Threshold velocity

Model equations for suffusion

➡ Open∇FOAM

"**Open**-source **F**ield **O**peration **A**nd **M**anipulation"
C++ toolbox involving customized numerical solvers



Model equations for suffusion

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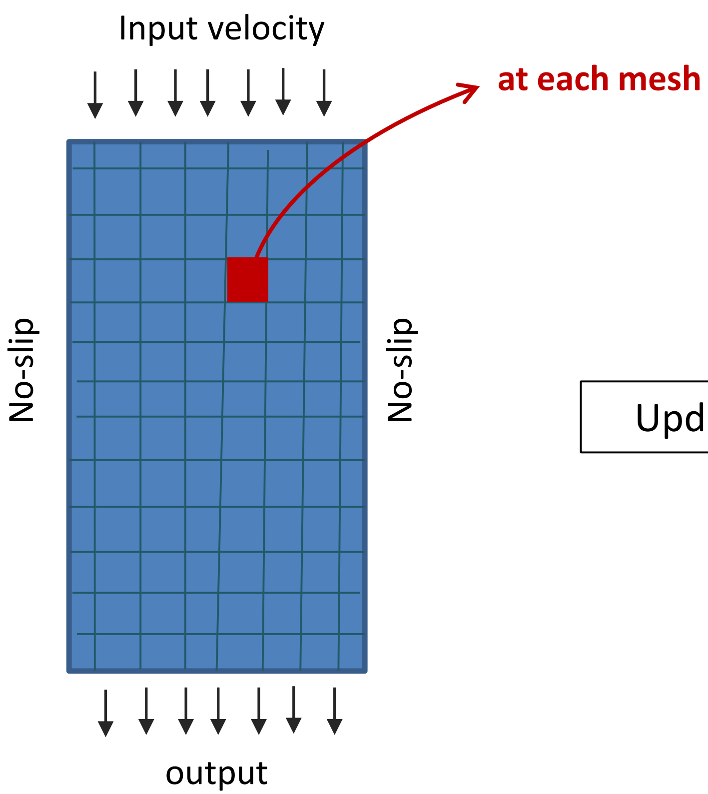


at each time step

Calculation of the flow

$$div(\vec{u})=0 \qquad u = -\frac{k}{\mu}\nabla p$$

Erosion law

$$\frac{\partial f}{\partial t} = -aef\left(\|u\| - u_t\right)$$

Update of the void ratio

$$e=\left((1-f)\frac{V_t}{V_c}\right)-1$$

Update of the permeability

$$k(f) = k(0)\frac{e(f)^3}{1+e(f)}\frac{1+e(0)}{e(0)^3}\left(\frac{1}{1+\left(\frac{d_c-d_f}{d_f}\right)f}\right)^2$$

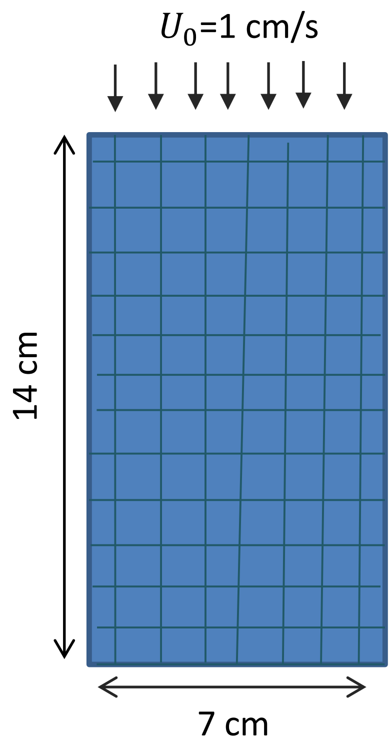
Internal channelization

Normal distribution $\boldsymbol{f} = \boldsymbol{f}_0 \pm \Delta \boldsymbol{f}$

Initially heterogeneous

d_f = 0.25 mm f_0 = 25%

d_c = 2 mm e_0 = 1.04



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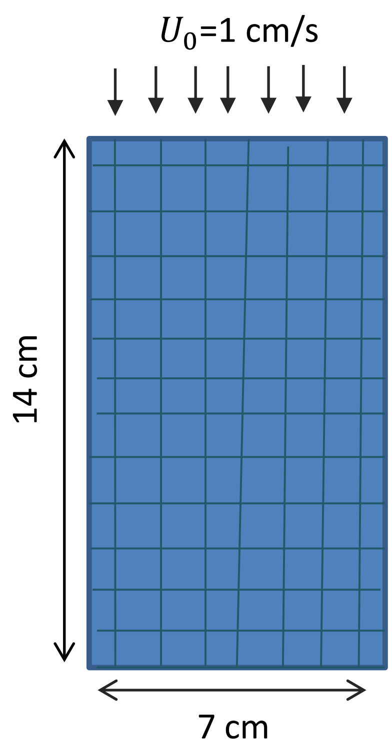
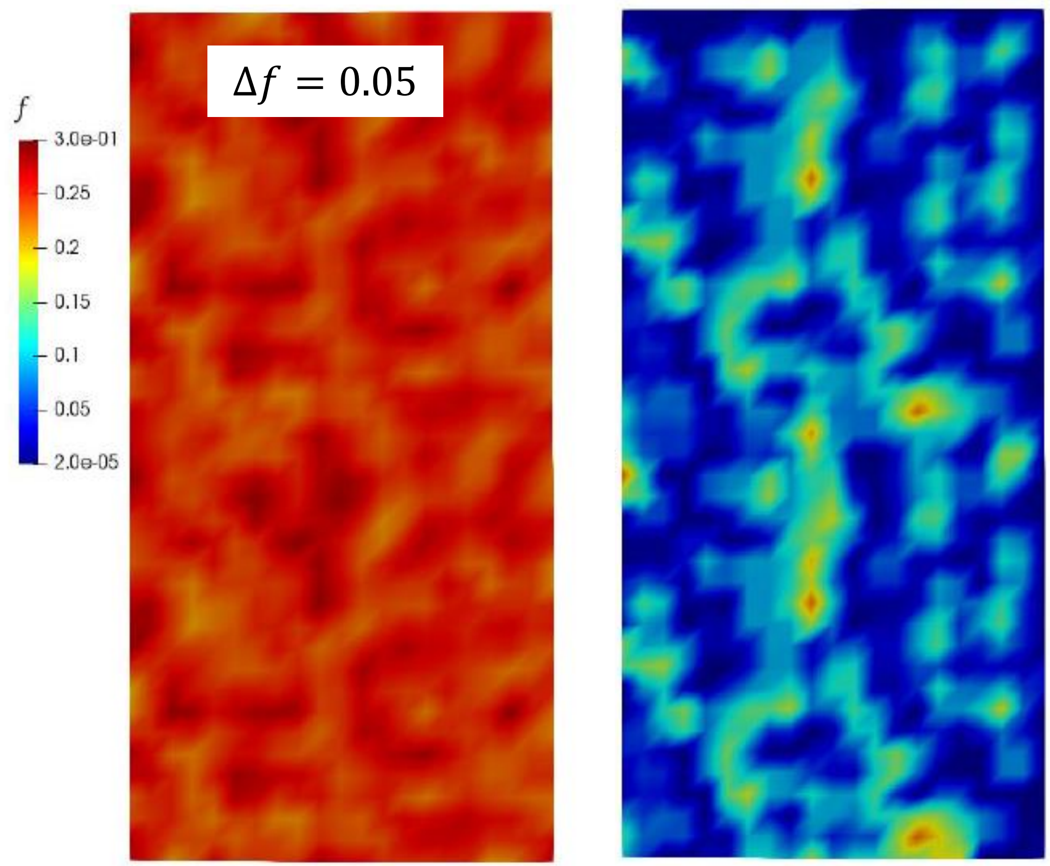


Initially heterogeneous

Channelization



t=0 s

t=1000 s

Internal channelization

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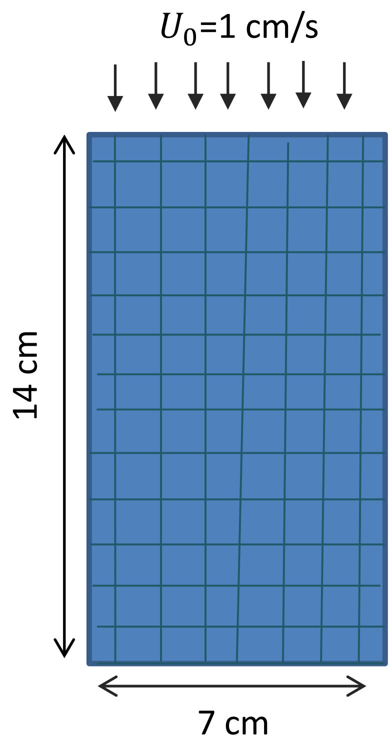

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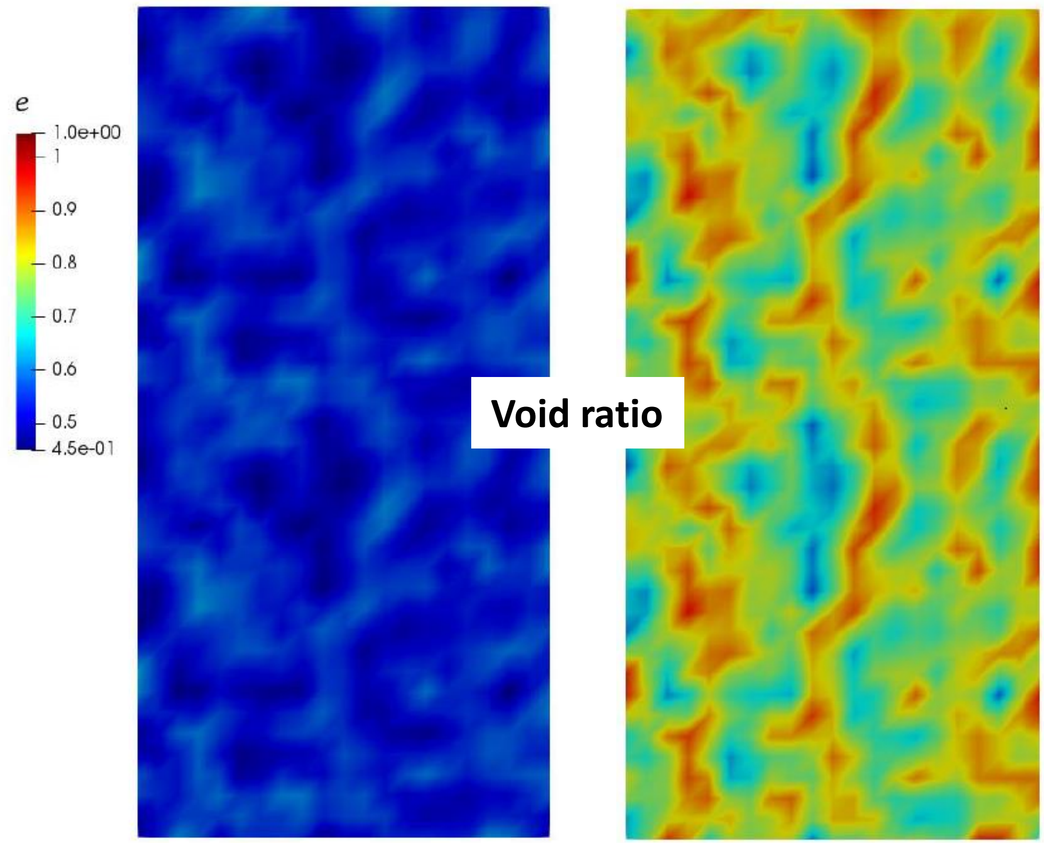
Channelization



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Internal channelization

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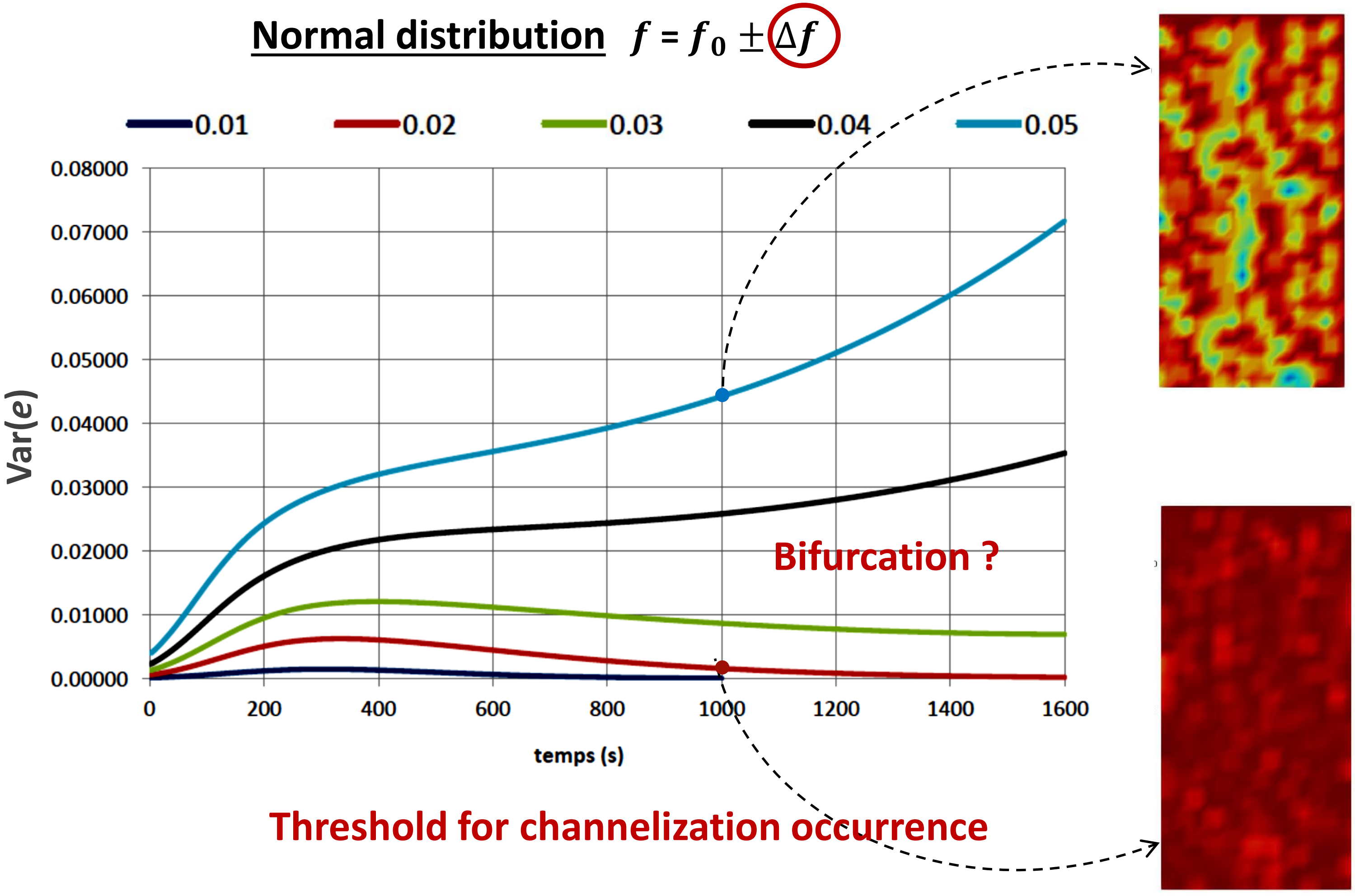
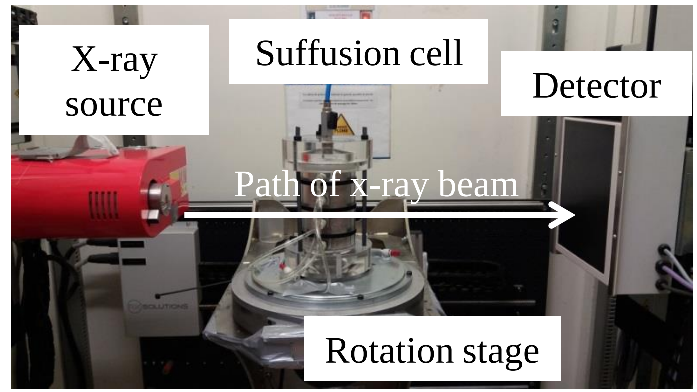


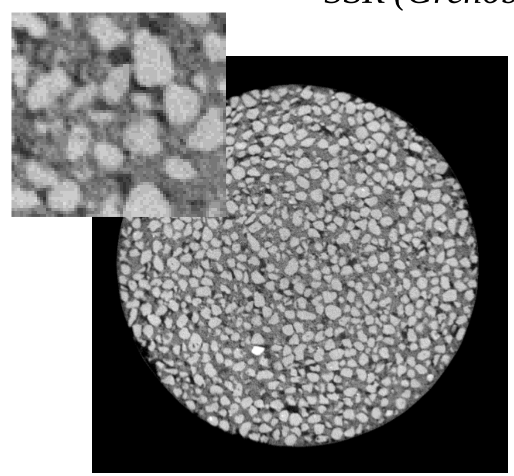
Comparison with experiments

Suffusion permeameter → X-ray tomography investigations

How about inside the sample?



3SR (Grenoble, France)



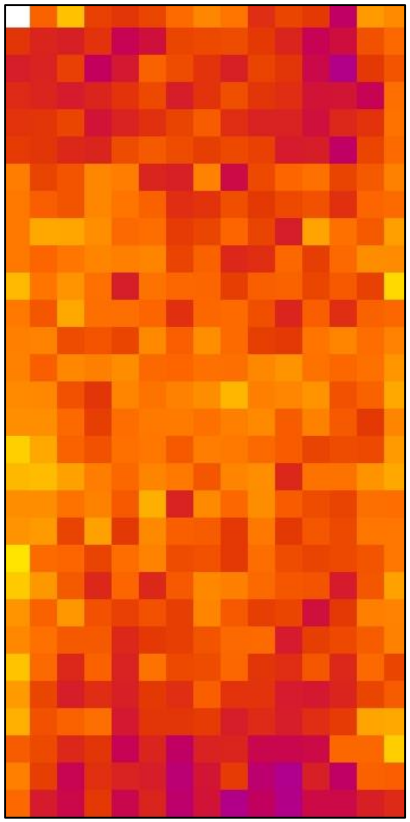
Micro-CT images

Nguyen *et al. Acta Geotech.* (2019)

Comparison with experiments

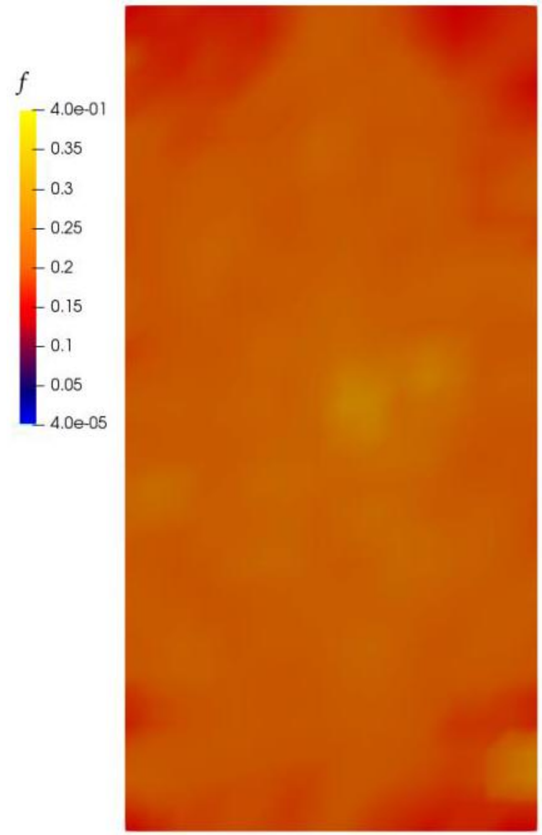
Before suffusion

Micro-CT data



High heterogeneities due to boundary conditions

Numerical modelling

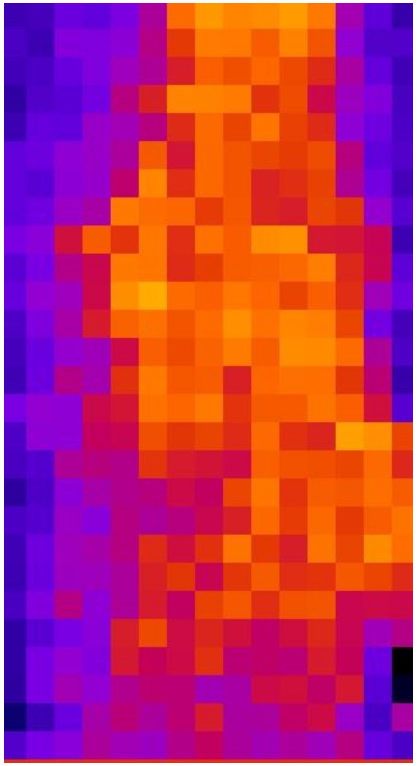


Input smoothed data

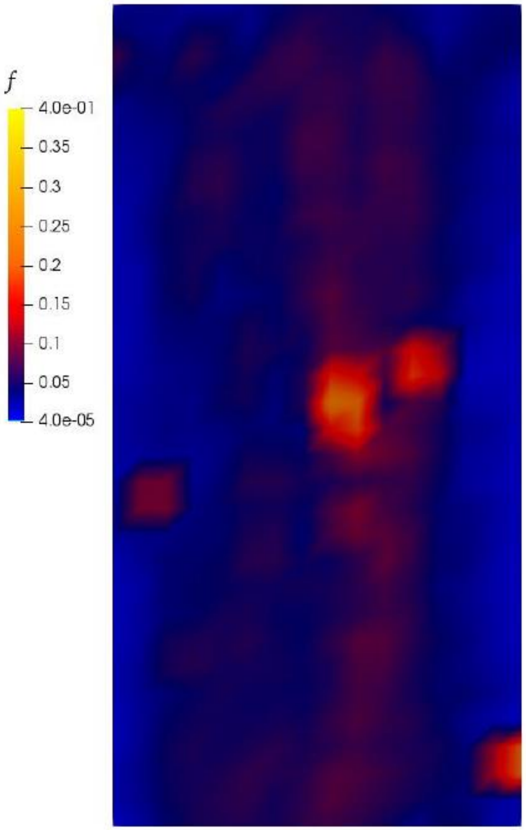
Comparison with experiments

After suffusion

Micro-CT data



Numerical modelling



➡ **Qualitative Agreement**

BUT

x Settlement is not taken into account

x Quantitative prediction – Calibration ?

Conclusion and Perspectives

Model equations for suffusion

Local erosion law $\frac{\partial f}{\partial t} = -ef(\|u\| - u_t)$

Local constitutive law for permeability $k(f) = k(0)\frac{e(f)^3}{1+e(f)}\frac{1+e(0)}{e(0)^3}\left(\frac{1}{1+\left(\frac{d_c-d_f}{d_f}\right)f}\right)^2$

Internal channelization

Triggered by a certain level of heterogeneity at the initial state

Normal distribution $f = f_0 \pm \Delta f$ → **Parametric study**

Comparison with micro-CT data

High shear intensity near the sample boundaries

Thank you for your attention